GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

April 6, 1966

Department of the Army
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

Attention: AMSMI-RSS
Research and Development Directorate

Subject: Monthly Letter 1, Project A-925
"Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes"
Contract No. DA-01-021-AMC-14464 (Z)
Covering the Period from March 1 to March 31, 1966

Gentlemen:

An existing aluminum tangent ogive radome mandrel, belonging to the U. S. Navy, was modified with permission, by removing the rear section of the tangent ogive and replacing this portion with a skirt having a slight taper. This resulted in a mandrel consisting of a tangent ogive section 13.23 inches in length and 7.45 inches in base diameter. This section was mated to a cone frustum section having an included angle of two degrees and a height of 6.25 inches. This resulted in a final mandrel height of 19.48 inches and a base diameter of 7.67 inches.

This mandrel was used to form a plaster mold to be used in slip-casting the required radomes. Initially 8 plaster molds were fabricated so that the required radomes could be cast without a releasing agent in the mold. Under these conditions each mold is good for only four castings. Radomes were pressure cast in a tip-up configuration to provide a more uniform wall thickness. As of 31 March 19 radomes have been cast of which 9 appear to be within the required final wall thickness tolerance of 0.63 ± 0.02-inch to within five inches of the tip. Three of the radomes have been fired and are within the tolerances shown in the attached drawing of final fired dimensions for the radomes.

Techniques have been worked out for flame glazing these radomes using arc plasma equipment and one out of tolerance dome has been glazed. At least three domes should be glazed and ready for shipment to GD/Pomona by April 13, 1966.

A sub-contract was initiated with General Dynamics/Pomona effective April 1, 1966, for design and installation of the required attachment system.

The fired radomes which have fallen outside the required tolerances have been used in a program to determine the erosion caused by lead pellets from a shotgun blast. The silica tips were cut off the domes and 3/4-inch base diameter stainless steel tips bonded to the domes with an epoxy adhesive. Radomes have been exposed to Number 9 shot (2mm diameter) from a 12 gauge shotgun. The shotgun muzzle to tip of radome distance was 11 feet. This gave an approximate shot velocity at the radome of 1200 fps. Properly mounted radomes have been shot six times with little, if any, damage to the radomes.

At the present time it is anticipated that nine radomes within the proper tolerances will be glazed and shipped to General Dynamics/Pomona by May 1, 1966.

Respectfully submitted,

J. N. Harris
Project Director

Approved:

J. D. Walton, Jr., Head
High Temperature Materials Branch

JNH/jw

Encl: Final Fired Dimensions
of SCFS Radomes

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

May 5, 1966

Department of the Army
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

Attention: AMSMI-RSS
Research and Development Directorate

Subject: Monthly Letter 2, Project A-925
"Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes"
Contract No. DA-01-021-AMC-14464 (Z)
Covering the Period from April 1 to April 30, 1966

Gentlemen:

All nine flame glazed slip-cast fused silica radomes were shipped to General Dynamics/Pomona by April 28, 1966. However, characterization data obtained on April 29, 1966 from the skirts of the last three domes shipped revealed a cristobalite content of 16 to 20 per cent. The first six radomes shipped had cristobalite content ranges of 5 to 10 per cent. It is felt that the three radomes having cristobalite contents greater than 16 per cent might give misleading results, therefore, three additional radomes have been prepared. These radomes are being flame glazed and the last of the three should be shipped to GD/Pomona by May 9, 1966.

The attachment system design by General Dynamics/Pomona is on schedule. All materials have been ordered and GD/P is attempting to provide a radome for the sled checkout test run scheduled on or about May 20th 1966.

Because of the temperatures to be encountered in the tip region of the radome General Dynamics/Pomona has decided that a Haynes Stellite high melting alloy will be necessary for the metal tip. The receipt of this material may require a priority order.

Respectfully submitted,

J. N. Harris
Project Director

Approved:

J. D. Walton, Jr., Head
High Temperature Materials Branch

JNH/js

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

July 6, 1966

Department of the Army
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

Attention: AMSMI-RSS
Research and Development Directorate

Subject: Monthly Letter 4, Project A-925
"Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes"
Contract No. DA-01-021-AMC-14464(Z)
Covering the Period from June 1 to June 30, 1966

Gentlemen:

The check-out run and three rain erosion tests at Holloman Air Force Base have been completed. The runs in the rain field were for 400, 800, and 2000 ft. All radomes survived the rain field runs, however, the metal tip on the radome used in the 800 ft rain field came off during the run and extensive erosion occurred in the blunted tip area.

These three radomes are being shipped to General Dynamics/Pomona for electrical boresight tests to compare the patterns before and after rain erosion.

The sled was damaged during the 2000 ft rain field run due to a malfunction in the first stage. The sled has been returned to the manufacturer for rebuilding and the remaining two sled tests will be conducted in 4000 and 6000 ft rain fields upon return of the sled to Holloman Air Force Base.

Respectfully submitted,

J. N. Harris
Project Director

Approved:

N. E. Poulos, Assoc. Head
High Temperature Materials Branch

JNH/jw

GEORGIA INSTITUTE OF TECHNOLOGY

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

August 15, 1966

Department of the Army
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

Attention: AMSMI-RSS
Research and Development Directorate

Subject: Monthly Letter 5, Project A-925
"Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes"
Contract No. DA-01-021-AMC-14464(Z)
Covering the Period from July 1 to August 12, 1966

Gentlemen:

The fourth rain erosion test was conducted at Holloman Air Force Base on August 11, 1966. The test was scheduled for a 4000 ft rain field, however, due to a loss of communications at the track the rain field was set up for 6000 ft. A decision was made to proceed with this test rather than lose the time required to change to a 4000 ft rain field. The test was initiated and the radome failed after traveling approximately 2000 ft in the rain field. The mechanism of failure is not known at this time but pieces of the radome recovered after the test indicate severe rain erosion damage.

A fifth test is scheduled for mid September, however, a decision as to the length of the rain field for this test has not been made as of this date.

Due to the time delay necessary for the final test it is suggested that a final report be prepared at this time on the basis of the tests already completed.

Respectfully submitted,

J. N. Harris
Project Director

Approved:

J. D. Walton, Jr., Head
High Temperature Materials Branch

JNH/js

GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

November 8, 1966

Department of the Army
U.S. Army Missile Command
Redstone Arsenal, Alabama 35809

Attention: AMSMI-RSS
Research and Development Directorate

Subject: Monthly Letter 6, Project A-925
"Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes"
Contract No. DA-01-021-AMC-14464(Z)
Covering the Period from August 13 to November 8, 1966

Gentlemen:

The Final Report, Part I was prepared and issued during this period. Also additional tooling was prepared and several fused silica radomes cast. From these radomes the best will be selected and shipped to General Dynamics, Pomona, California for installation of the metal tip and attachment ring. The two sled adapters have been recoated with ablative material.

The final radome rain erosion sled test has been scheduled for December 2, 1966. The schedule of events leading to this test are as follows:

1. Shipment of coated adapter number one from General Dynamics/ Pomona to Holloman Air Force Base; November 9, 1966.

2. Vibration tests of radome on coated adapter number two conducted at General Dynamics/Pomona; November 9-18, 1966.

3. Shipment of coated adapter number two from General Dynamics/Pomona to Holloman Air Force Base, November 18, 1966.

4. Shipment of Slip-Cast Fused Silica Radome from Georgia Tech to General Dynamics/Pomona, November 10, 1966.

FINAL TECHNICAL REPORT
PART I

PROJECT A-925

RAIN EROSION SLED TESTING OF SLIP-CAST FUSED SILICA RADOMES

J. D. WALTON, JR. AND J. N. HARRIS

Contract DA-01-021-AMC-14464(Z)

Prepared for
U. S. Army Missile Command
Redstone Arsenal

October 1966

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia

FINAL TECHNICAL REPORT
PART I

PROJECT A-925

RAIN EROSION SLED TESTING OF SLIP-CAST FUSED SILICA RADOMES

By

J. D. WALTON, JR. and J. N. HARRIS

CONTRACT DA-01-021-AMC-14464(Z)

28 FEBRUARY to 21 SEPTEMBER 1966
Issued October 1966

Performed for
DEPARTMENT OF THE ARMY
U. S. ARMY MISSILE COMMAND
Redstone Arsenal, Alabama 35809

ABSTRACT

This report describes a rocket sled test program which was conducted to determine the rain erosion resistance of slip-cast fused silica at velocities above 5000 feet per second. The fabrication techniques used at the Georgia Institute of Technology to slip-cast, heat treat and flame glaze the radomes are discussed. The results of the six sled tests which were run at Holloman Air Force Base, New Mexico, and which covered distances up to 4000 feet in an artificial rain field of 2-1/2 inches per hour are presented. The failure of two radomes to survive rain damage for distances between 2000 and 4000 feet in the rain field is attributed to the severe mechanical environment which results from sled vibration. This condition is considered extremely unrealistic with respect to a missile flight situation. It is concluded that flame glazed slip-cast fused silica should survive a minimum of 4000 feet in a natural rain of 2-1/2 inches per hour under actual missile flight conditions. It is recommended that at least one additional sled test be run. The slip-cast fused silica radome should be unglazed since simulated rain erosion testing has suggested that the rain damage should be less severe for the unglazed than for the glazed radome. Also, recommendations are made concerning means for reducing the vibration provided by the rocket sled.

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TABLE OF CONTENTS (Continued)

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LIST OF TABLES

I. PURPOSE

The purpose of Contract DA-01-021-AMC-14464(Z) is to study the behavior of slip-cast fused silica radomes operating in a rain environment at velocities near Mach 5.

II. BACKGROUND

One of the most perplexing problems associated with high speed missile flight is rain erosion. It has been investigated generally for over twenty years and the mechanism of rain damage has been studied specifically for over a decade. Nevertheless, the problem remains unsolved. Also, little hope is voiced that a solution will be found in the near future that will quantitatively relate the properties of a material to its response to supersonic rain impact. A recent report by Wahl reviews the current state of the art 1/.

Slip-cast fused silica has been considered recently for several hypersonic missile radome applications. It is unique among current radome materials in that it combines excellent thermal shock resistance with excellent electrical properties, ease of fabrication, low thermal conductivity, and low cost. The properties of slip-cast fused silica suggest that it should perform thermally and electrically up to Mach 6 or 7 at low altitude. Performance at higher speeds would be limited only by the ablation and the electromagnetic signal attenuation. Therefore, slip-cast fused silica has the potential of functioning as a radome over the range of environments extending from supersonic missiles to reentry bodies. Only one property of this material remains to be established over this wide range of velocities, and that is its rain erosion resistance.

Early in 1963 slip-cast fused silica radomes were evaluated for rain erosion resistance on the SNORT rocket sled track at the Naval Ordnance Test Station, China Lake, California 2/. These tests indicated that pointed fused silica radomes were satisfactory at velocities up to Mach 2.7 (maximum velocity of test). The artificial rainfall for these tests contained an average drop size of 2.0 millimeters with a rate of 2 inches per hour. The length of the rain field was 2500 ft.

III. INTRODUCTION

This program was undertaken to determine the rain erosion resistance of slip-cast fused silica at Mach 5. The rocket sled track at Holloman Air Force Base, New Mexico was selected as the site for the tests. The two stage sled was designed and constructed by Inca Engineering Corporation, San Gabriel, California. The radomes were fabricated and glazed at the Georgia Institute of Technology, Atlanta, Georgia. General Dynamics/Pomona Division provided the metal tip and attachment system and conducted electrical and mechanical tests on the finished radomes. Georgia Tech was responsible for monitoring all tests and documenting the test results.

This report (Part I) summarizes the results of the sled tests at Holloman Air Force Base, New Mexico, carried out during the period 27 June through 21 September 1966. Part II covers (a) the assembly of the metal tip and attachment to the radome, (b) the mechanical and boresight testing of the completed radome assembly, and (c) boresight testing of the radomes after the sled tests. Part III presents the results of the sled tests performed after 21 September 1966.

IV. THE TEST PROGRAM

A. The Radome

Figure 1 shows the radome configuration that was selected. This test shape provides the front 13 inches of an ogival radome approximately 31 inches long and 13-3/4 inches in base diameter. The entire radome could not be used because of the weight restrictions imposed by the sled design. However, it was decided that the rain damage would be most severe on the front 1/3 of the radome and that this frontal area could be provided by the smaller radome.

From Mach 2.7 rain erosion tests run at NOTS 2/ it was decided that a metal tip would be used at the stagnation point. This would eliminate any raindrop impingement normal to the radome surface. It was also decided that the surface of the radome would be flame glazed since flame glazed slip-cast fused silica radomes had provided more resistance to rain erosion damage than the unglazed radomes.

The attachment and tip design, as provided by General Dynamics/Pomona, is shown in Figure 2.

B. The Rocket Sled

The two stage rocket sled is shown in Figure 3. The first stage is a Cajun rocket motor and the second stage is a Gila IV motor. The first stage accelerates the vehicle to about 1200 feet per second, at which point the second stage ignites and accelerates the sled to a design velocity of about 5600 feet per second. The typical sled velocity is shown as a function of time and distance from launch in Figure 4. The sled and radome are shown in Figure 5.

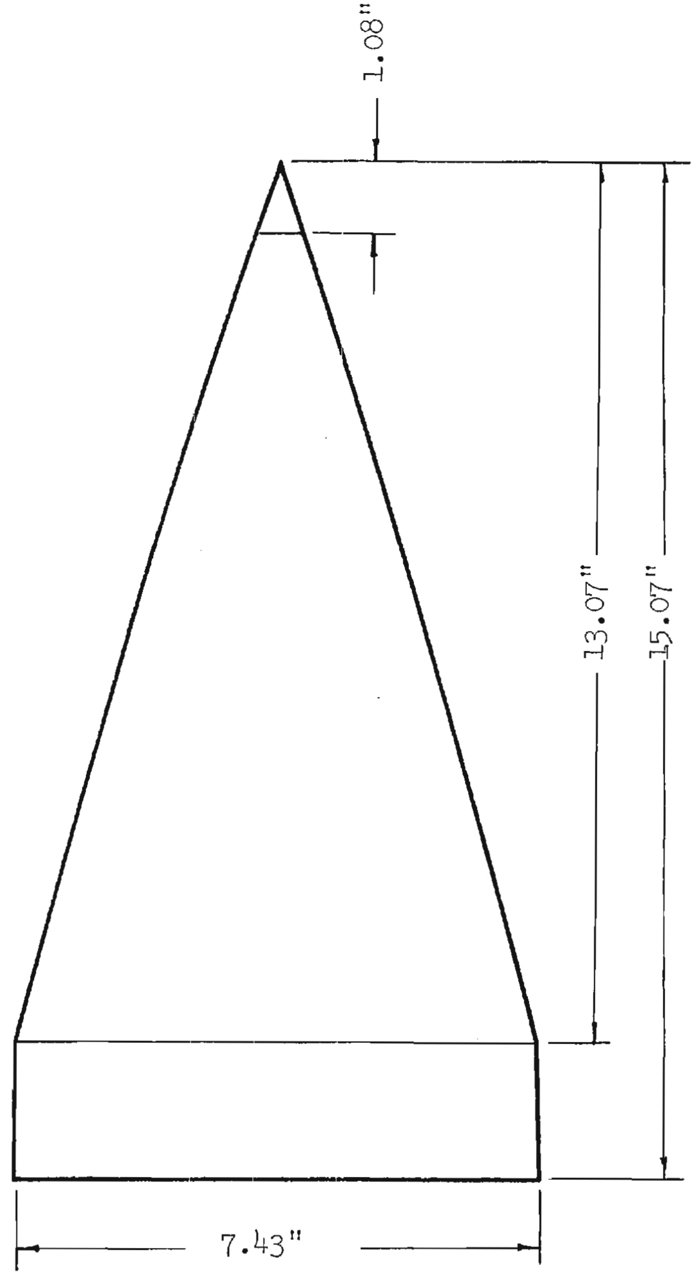

Figure 1. Radome Configuration for Mach 5 Rain Erosion Sled Tests.

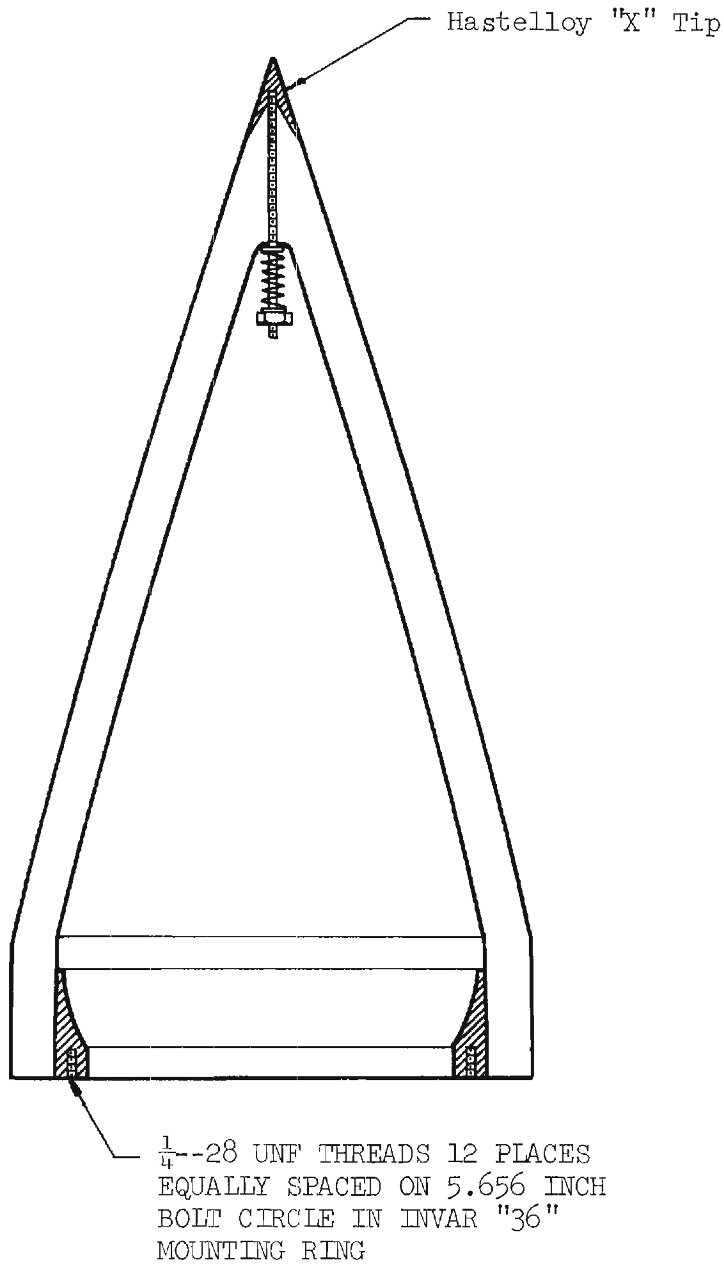

Figure 2. Radome Assembly Showing Tip and Attachment Design.

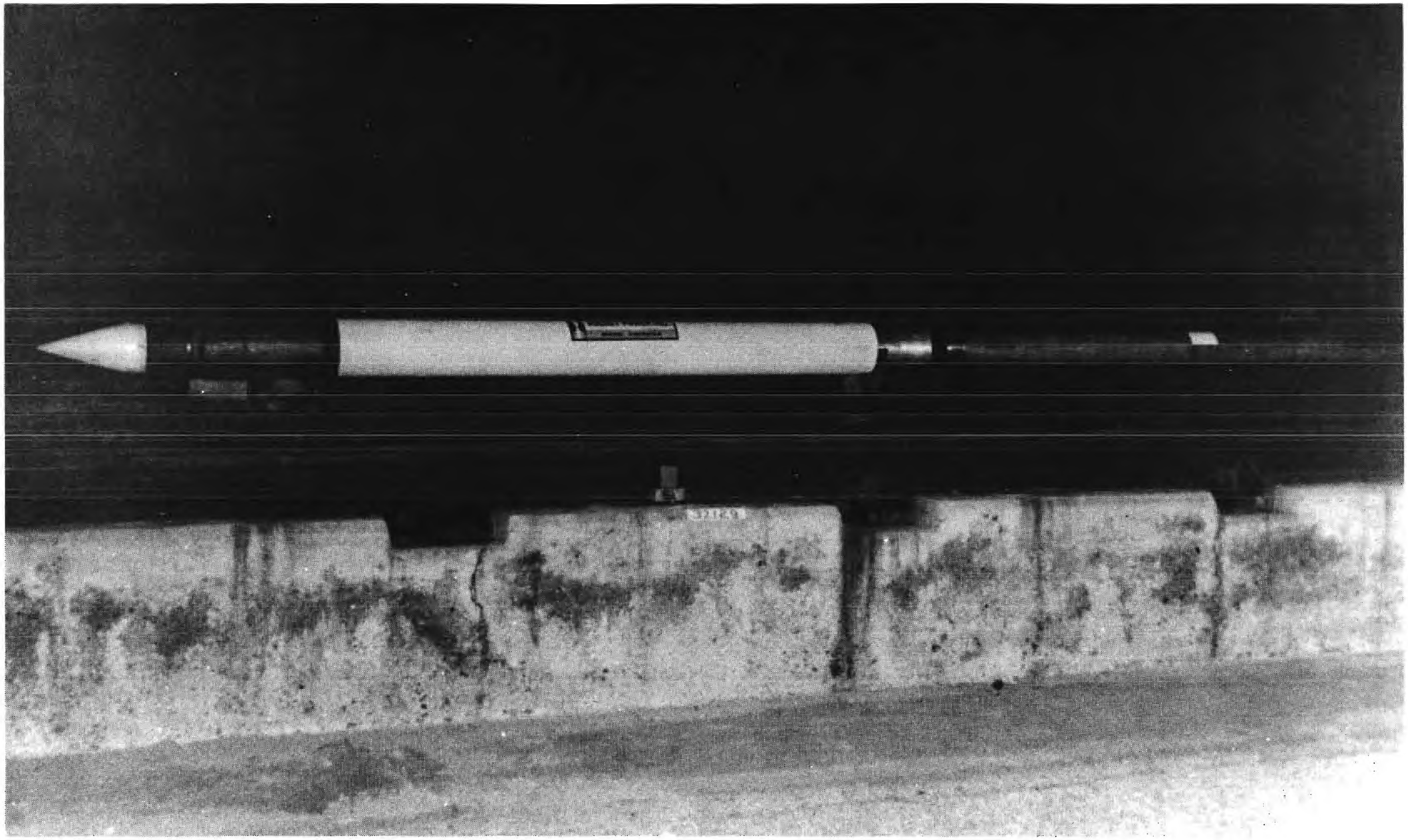

Figure 3. Two Stage Rocket Sled Used in Mach 5 Rain Erosion Sled Tests.

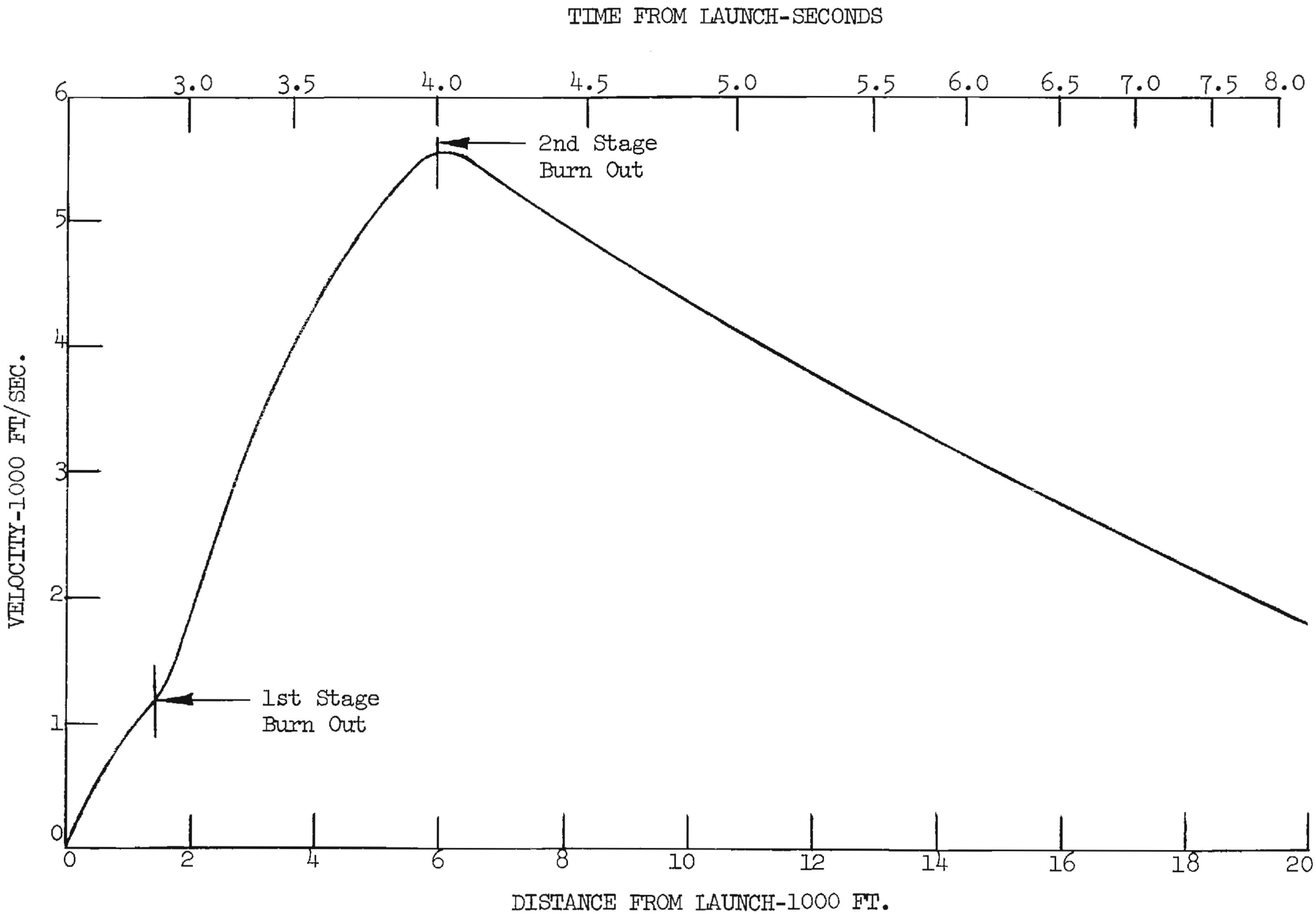

Figure 4. Typical Sled Velocity vs Distance and Time from Launch.

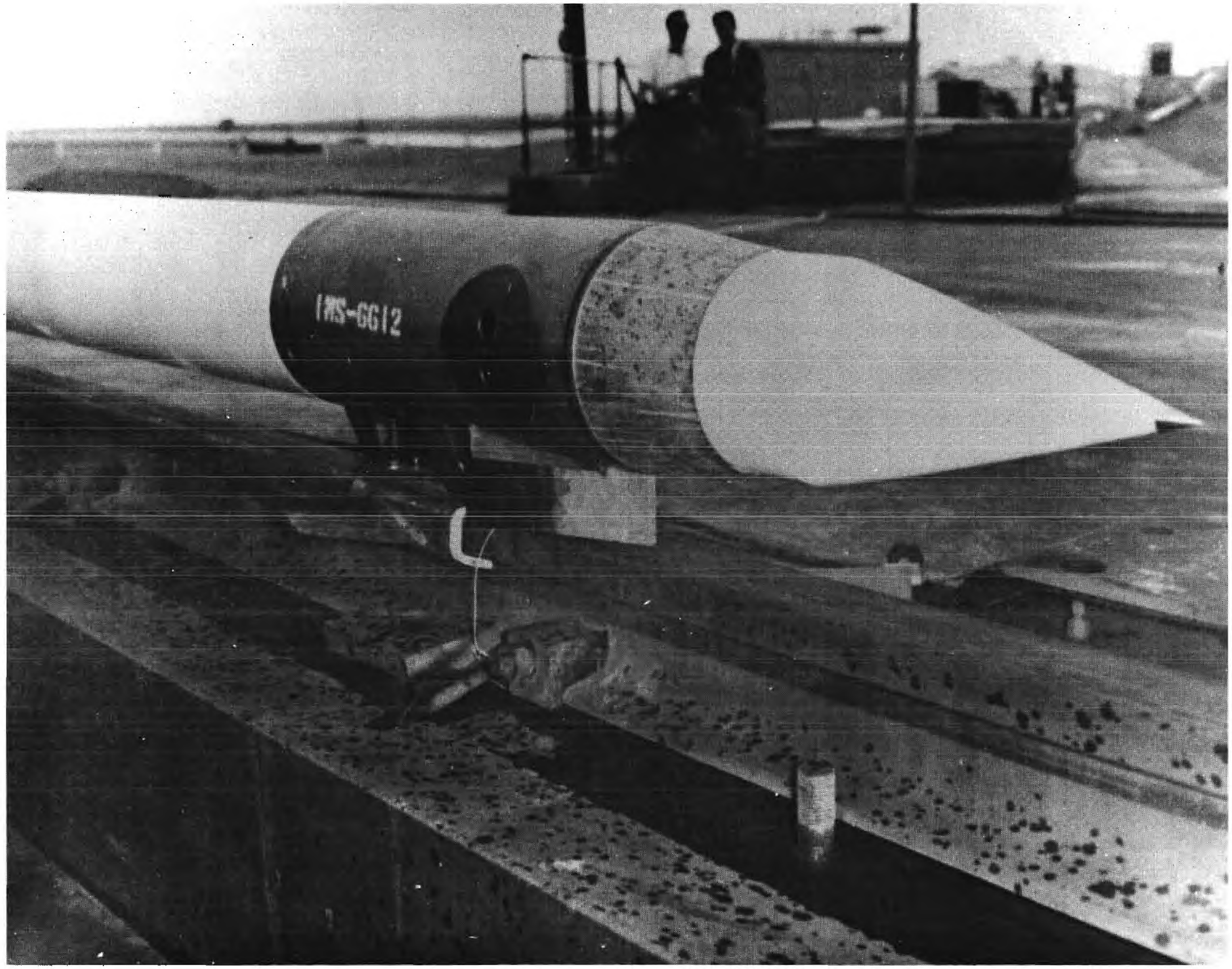

Figure 5. Close-up of Sled on the Track Showing Radome and Transition Piece.

C. The Test Track Facility

The Holloman facility provides 35,000 feet of test track with a rain field of 6000 feet. The rain section is located so that there are 8000 feet of track for acceleration of the vehicle and 21,000 feet for deceleration. The simulated rain is supplied by spraying sections 400 feet long. Each section contains 50 spray heads spaced 8 feet apart. The length of the rain field can be adjusted to provide any whole multiple of 400 feet 3/.

D. The Test Environment

The tests were designed so that the peak velocity would be obtained in the rain field. The rain rate was adjusted to be 2-1/2 inches per hour with no wind blowing. The average drop size was between 1.5 and 2 millimeters. The programed rain environment of each sled run is given in Table I.

TABLE I

RAIN ENVIRONMENT SCHEDULE FOR SLED TESTS

Run No.	Holloman Number	Rain Field	Date Run
1	7RA2A	None	June 27
2	7RB1	400	June 30
3	7RC1	800	June 30
4	7RD1	2000	July 1
5	7RE1	4000	August 11
6	7RE2A	4000	September 21

V. EXPERIMENTAL WORK

A. Fabrication of Test Radomes

The test radomes were slip-cast from a fused silica slip purchased from Glasrock Products, Incorporated. The slip-casting was carried out in plaster molds using pressure casting techniques.

1. Mandrel Modification

An existing tangent ogive aluminum mandrel, approximately 31 inches high with a base diameter of 13 inches, was available for this work. The mandrel was constructed under a Navy contract and was modified, with Navy approval, to provide the desired radome shape for the sled tests.

This mandrel was separated into two sections at a point where the base diameter of the front ogival section was 7.447 inches. Three circular aluminum sections two inches in thickness and one section one inch in thickness were pinned together and attached to the existing front section of the radome to form a base extension for the necessary attachment. This extension section was machined to mate with the base of the radome in the shape of a cone-frustum having a one degree taper.

2. Mold Fabrication

The necessary molds were fabricated using U. S. Gypsum Pottery Plaster No. 1. All molds were made with 91.6 pounds of water and 114.4 pounds of plaster. In all cases, slaking time was 4 minutes and mixing time was 5 minutes. Water was allowed to remain in the mixing tank sufficiently ahead of mixing time for the water to come to room temperature before adding the plaster. All molds were serially numbered and records were kept with each casting made in each mold.

3. Techniques of Slip-Casting and Firing

All casting was carried out under pressure in order to reduce the time necessary to slip-cast the thick wall required (about 0.63-inch). Each plaster mold was provided with a steel cover plate having the necessary fittings for pressure casting. A typical setup for pressure slip-casting is shown schematically in Figure 6. Pressure was applied to the slip reservior at 10 psi for 10 minutes to allow the mold to fill completely and to allow the displaced air to escape through the plaster mold. Air pressure was then increased to 20 psi for the remainder of the casting period. All casting was carried out with the mold in the tip-up position.

In spite of the precautions taken in mold fabrication it was necessary to establish a casting time to produce the required 0.63-inch radome wall thickness for each mold. No mold release was used and only 3 castings were made in each mold before it was discarded.

The initial casting in each mold was based on the proper casting time found for the previous mold. A casting was made in the new mold and the dry wall thickness measured. If it was not within tolerance it was corrected using the formula:

$$\theta_2 = \theta_1 \frac{W_2^2}{W_1^2}$$

where: θ_1 = Initial casting time

θ_2 = New casting time

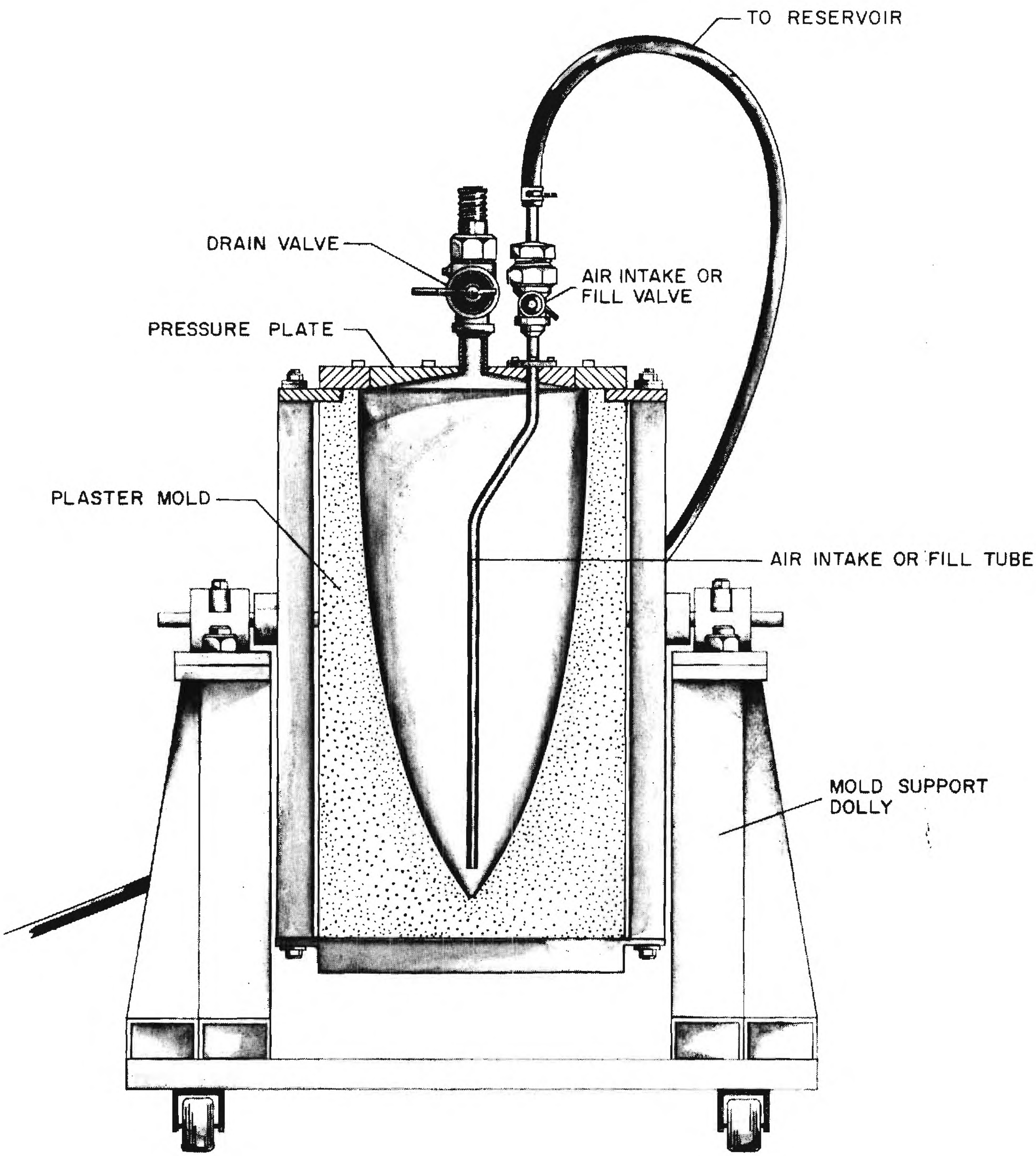

Figure 6. Typical Pressure Casting Setup for Slip-Casting Fused Silica Radome.

W_1 = Initial radome wall thickness

W_2 = Desired radome wall thickness

and a new casting made.

Each radome was allowed to dry 2 to 3 hours in the mold before handling. All radomes were handled with clear plastic gloves and were not touched with the hands until after heat treatment. This step is necessary to prevent localized devitrification of the radome surface from impurities, particularly sodium chloride from perspiration from the hands.

After removal from the mold each radome was dried for several days at room temperature and then heat treated in an electrical resistance heated furnace. Three radomes were heat treated at one time on a rotating pedestal within the furnace. The three radomes were placed on blankets of aluminum-silicate fibers and arranged on the pedestal in the furnace as shown in Figure 7. The heat treating schedule was as follows: 400° F for 4 hours, 1800° F for 16 hours, 1900° F for 4 hours, 2300° F for 2 hours 25 minutes. The furnace then was turned off and allowed to cool to 400° F before opening.

The qualified heat treated radomes had the configuration and tolerances shown in Figure 8. The wall thickness was measured utilizing the apparatus shown in Figure 9, and the radomes were then epoxy bonded to an aluminum base plate and set up in a lathe. Roundness measurements were made and the radome skirt cut off at the point shown in Figure 8. The skirt was used to obtain modulus of rupture (MR) and volume per cent cristobalite present in each radome. Cristobalite data and MR were obtained from each quadrant of the skirt to assure that the heat treating arrangement shown in Figure 7 had given

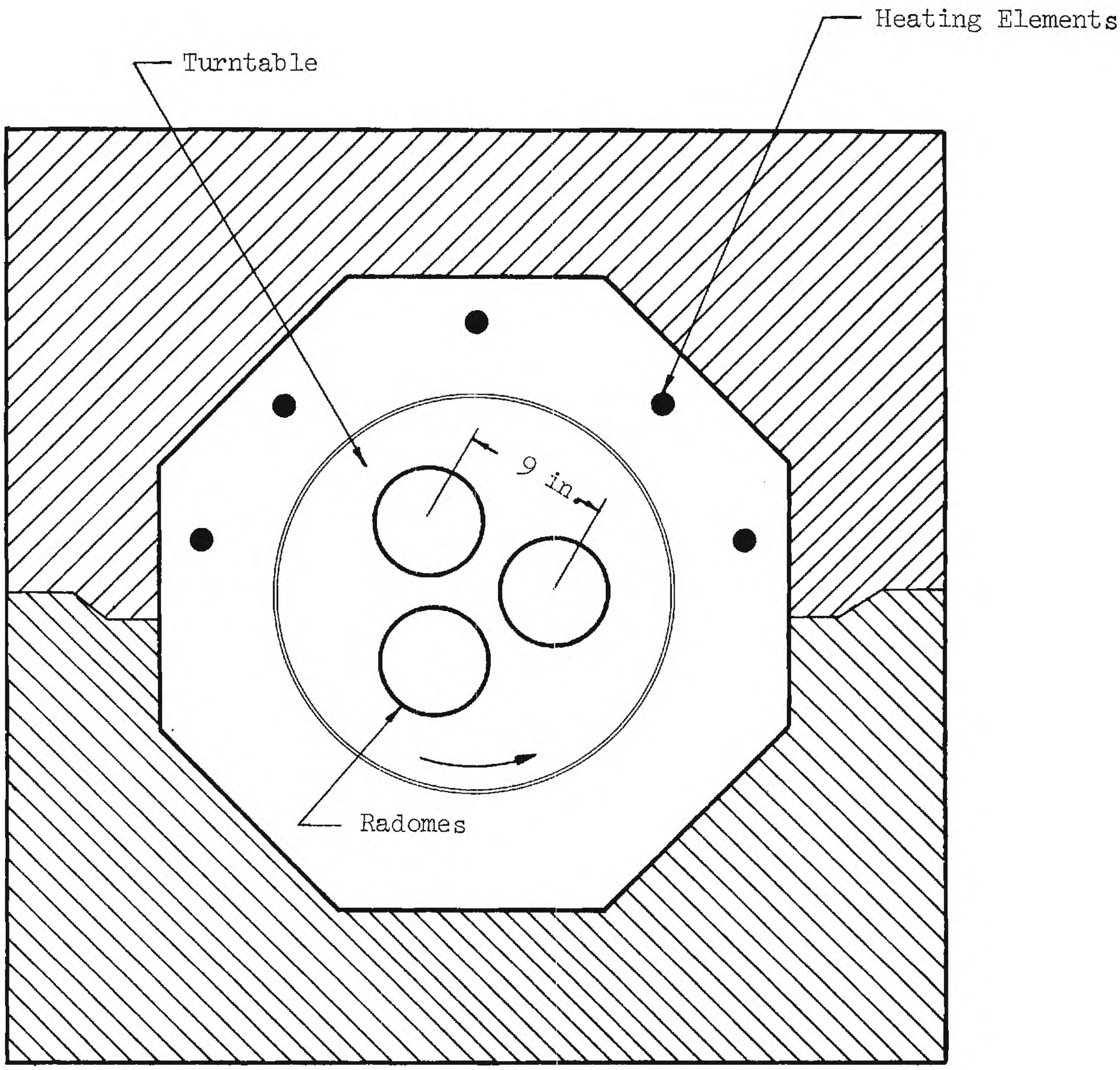

Figure 7. Schematic of Arrangement Used in Heat Treating Radomes in Furnace.

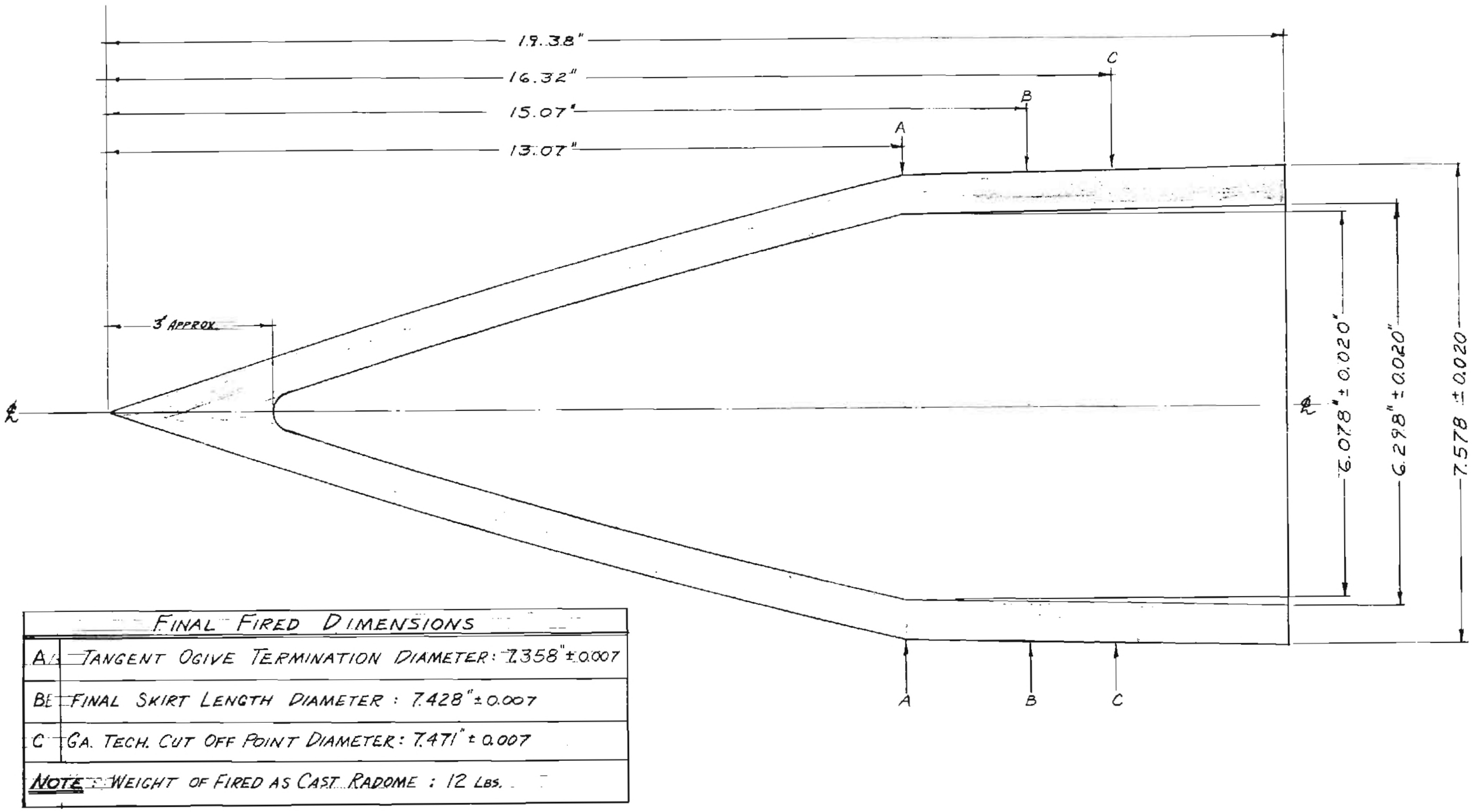

Figure 8. Configuration and Tolerances Used to Qualify Heat Treated Radomes.

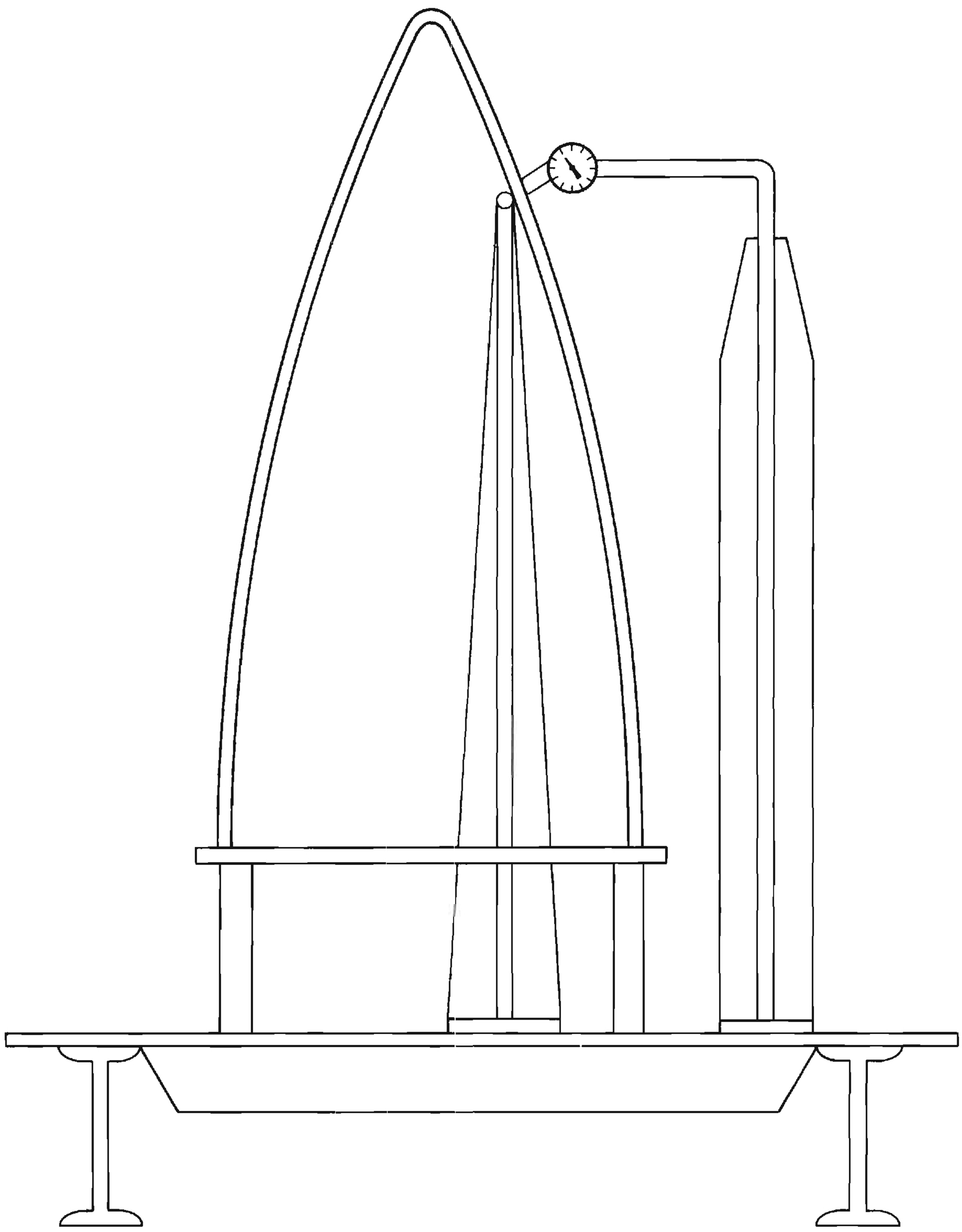

Figure 9. Drawing Illustrating Apparatus Used to Measure Wall Thickness of Radome Shapes up to Four Feet High.

a uniform heat treatment to all points of the radome. In addition, out of tolerance radomes were heat treated and the entire radome cut into MR specimens to assure that the radomes were receiving uniform heat treatment over their vertical length. Modulus of rupture specimens were broken transversely in center point loading on a three inch span and at a loading rate of 600 lb/minute. The broken MR specimens were ground to pass a 325 mesh screen (44 μ) and used for x-ray diffraction determination of cristobalite content. Table II shows the average MR and cristobalite content with 95 per cent confidence interval of the radomes used in the rain erosion test program.

TABLE II

HISTORY OF RADOMES SHIPPED TO GD/P FOR SELECTION OF FINAL TEST RADOMES AND INSTALLATION OF ATTACHMENT SYSTEM

Radome Serial No.	Mold No.	Casting Time	Skirt Wall Thickness North	East	South	West	Modulus of Rupture	Bulk Cristobalite
		(min)	(in)	(in)	(in)	(in)	(psi)	(v/o)
1007	314	170	0.633	0.649	0.643	0.651	4764 ± 264	7.0 ± 1.0
1612	412	181	0.647	0.647	0.652	0.651	4642 ± 405	7.7 ± 0.1
2723	614	180	0.633	0.634	0.634	0.637	4501 ± 299	9.1 ± 0.8
1411	411	155	0.639	0.639	0.648	0.645	4850 ± 398	8.3 ± 0.4
3327	712	170	0.609	0.603	0.617	0.622	4315 ± 500	9.7 ± 1.0
3430	811	170	0.617	0.640	0.647	0.649	---	8.7 ± 2.0

The satisfactory radomes were flame glazed using a plasma jet to fuse the surface. This provided a coating of nonporous fused silica that served to seal the surface. This thickness of the fused layer varied from about 0.030 to 0.040-inch near the tip to less than 0.005-inch near the base of the radome.

The flame glazed radomes were sent to General Dynamics/Pomona for installation of the attachment ring, and metal tip. The radome assemblies were subjected to vibrational proof tests and boresight tests and then shipped to Holloman Air Force Base for rain erosion sled tests. The domes that survived the rain test were returned to GD/P for subsequent boresight tests (Part II).

VI. RAIN EROSION SLED TEST RESULTS

Table III summarizes the sled tests carried out at Holloman Air Force Base during the period 27 June through 21 September 1966.

TABLE III

SUMMARY OF RAIN EROSION TEST RESULTS

Run No.	Holloman No.	Radome Serial No.	Rain Field (ft)	Rain Entrance Velocity (ft/sec)	Rain Exit Velocity (ft/sec)	Maximum Velocity (ft/sec)	Remarks
1	7RA2A	1007	None	----	----	5530	Radome hit bird during coast out at about 1500 ft/sec.
2	7RB1	2723	400	5250	5350	5443	Erosion effects consisted of surface dimples covering about 50% of the surface.
3	7RC1	1411	800	5400	5550	5599	The first 3-1/2 inches of the radome were lost when the sled hit the water brake. Surface erosion was twice Run No. 2.
4	7RD1	3430	2000	5050	4600	5100	Moderate surface erosion resulted from rain impingement.
5	7RE1	1612	4000	5200	---	5420	The radome broke up after about 2000 ft in the rain.
6	7RE2A	3327	4000	4870	---	5345	The radome broke up after about 3000 ft in the rain.

A. Run No. 1 (7RA2A)

Figure 10 shows radome No. 1007 after impact with a bird. From image motion photographs it could be seen that the radome was undamaged until the bird was hit. From velocity profile data obtained from this run it was estimated that the sled had coasted to a speed of about 1500 ft/sec when it hit the bird.

B. Run No. 2 (7RB1)

Figures 11, 12, and 13 show radome No. 2723 after exposure to 400 feet of rain. From these photographs it can be seen that practically every drop caused some surface damage. No other damage was observed.

C. Run No. 3 (7RC1)

Figures 14 and 15 show radome No. 1411 after exposure to 800 feet of rain. The broken tip suggested that the radome probably broke during or upon leaving the rain field. At this time sled vibration would be at a maximum. However, from the image motion photograph shown in Figure 16 it can be seen that the radome was intact when it emerged from the rain field. It can also be seen that the drag brakes (cylindrical piece protruding from the side of the sled just aft of the transition piece which connects the radome to the sled) are almost completely extended. This information suggested that the radome tip probably survived the high velocity portion of the flight and that the portion of the radome may have come off as a result of the high deceleration associated with the sled hitting the water brake. Subsequent search of the water brake area uncovered the broken tip about 800 feet from the point where the sled first encountered the water brake.

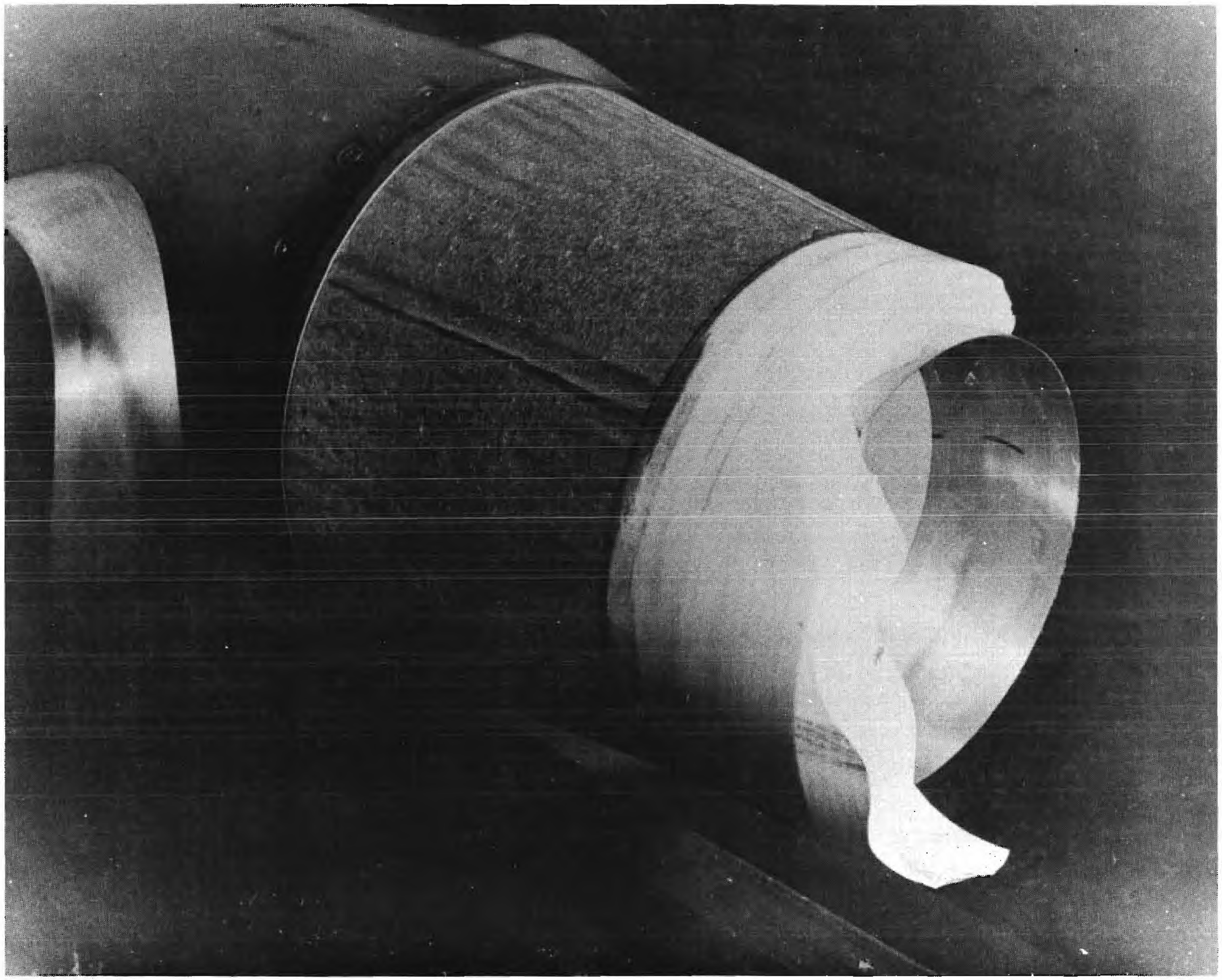

Figure 10. Radome from Run No. 1 after Hitting Bird (7RA2A).

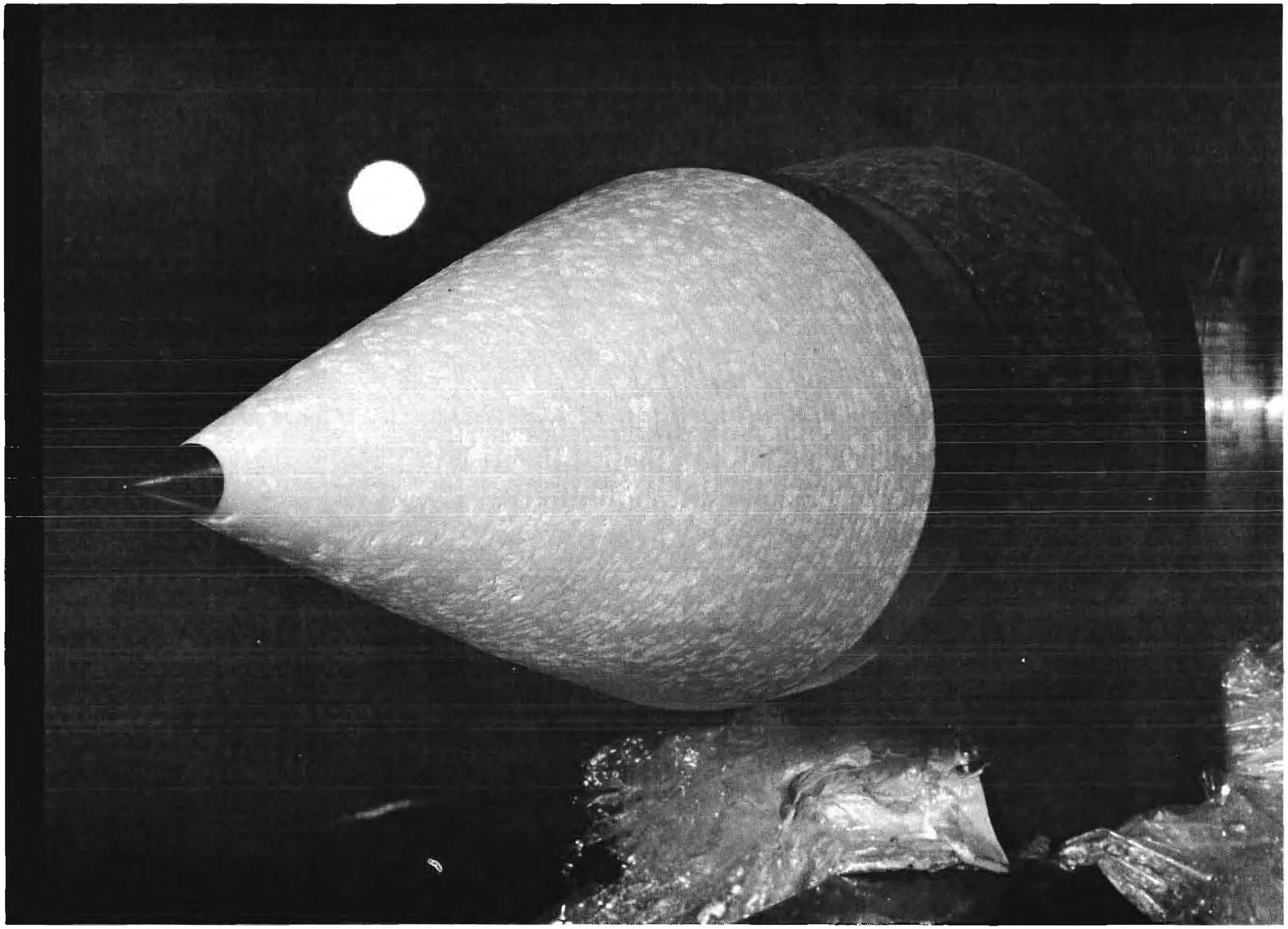

Figure 11. Radome on Sled after 400 Feet of Rain in Run No. 2 (7RB1).

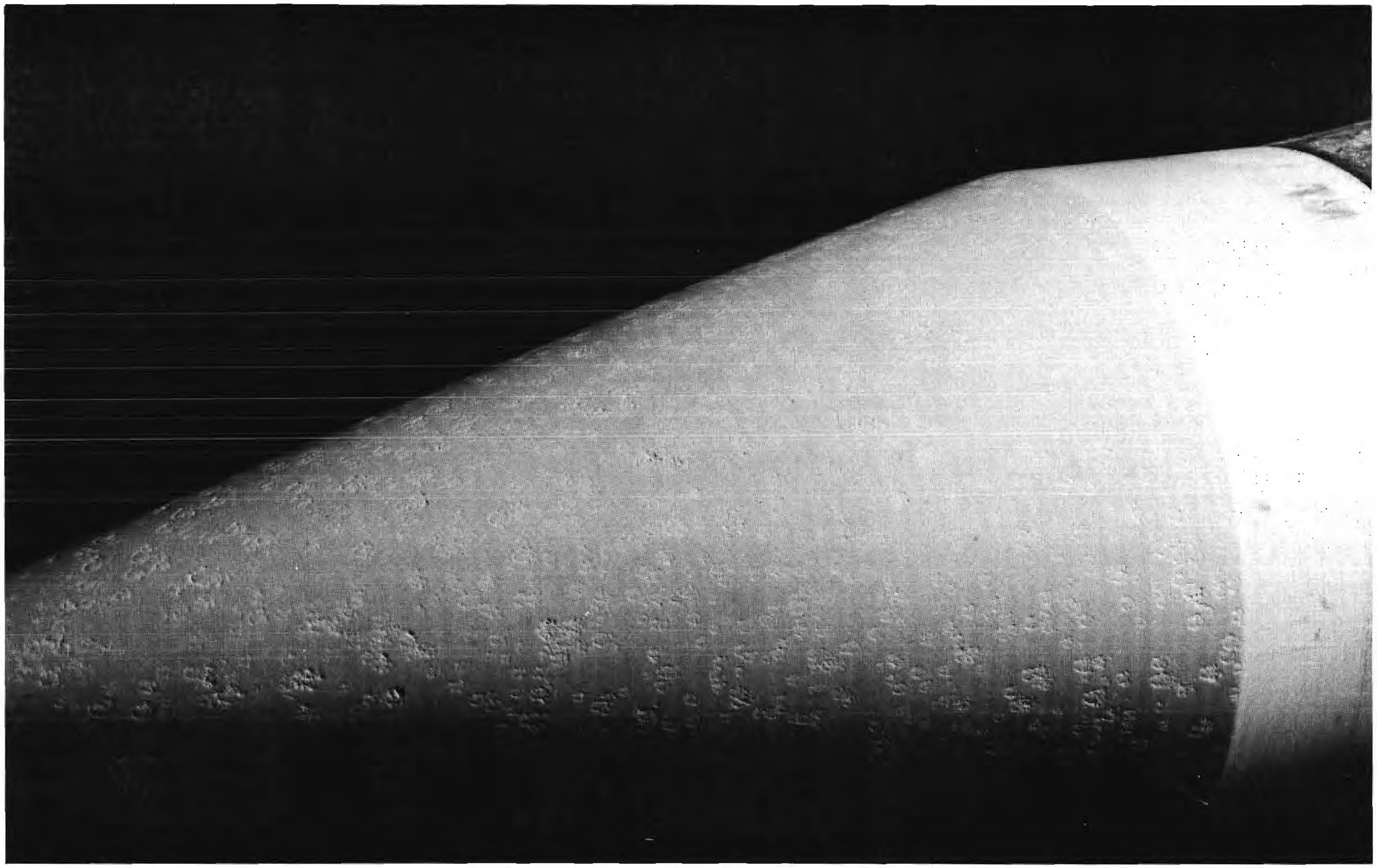

Figure 12. Close-up of Radome from Run No. 2 (7RB1).

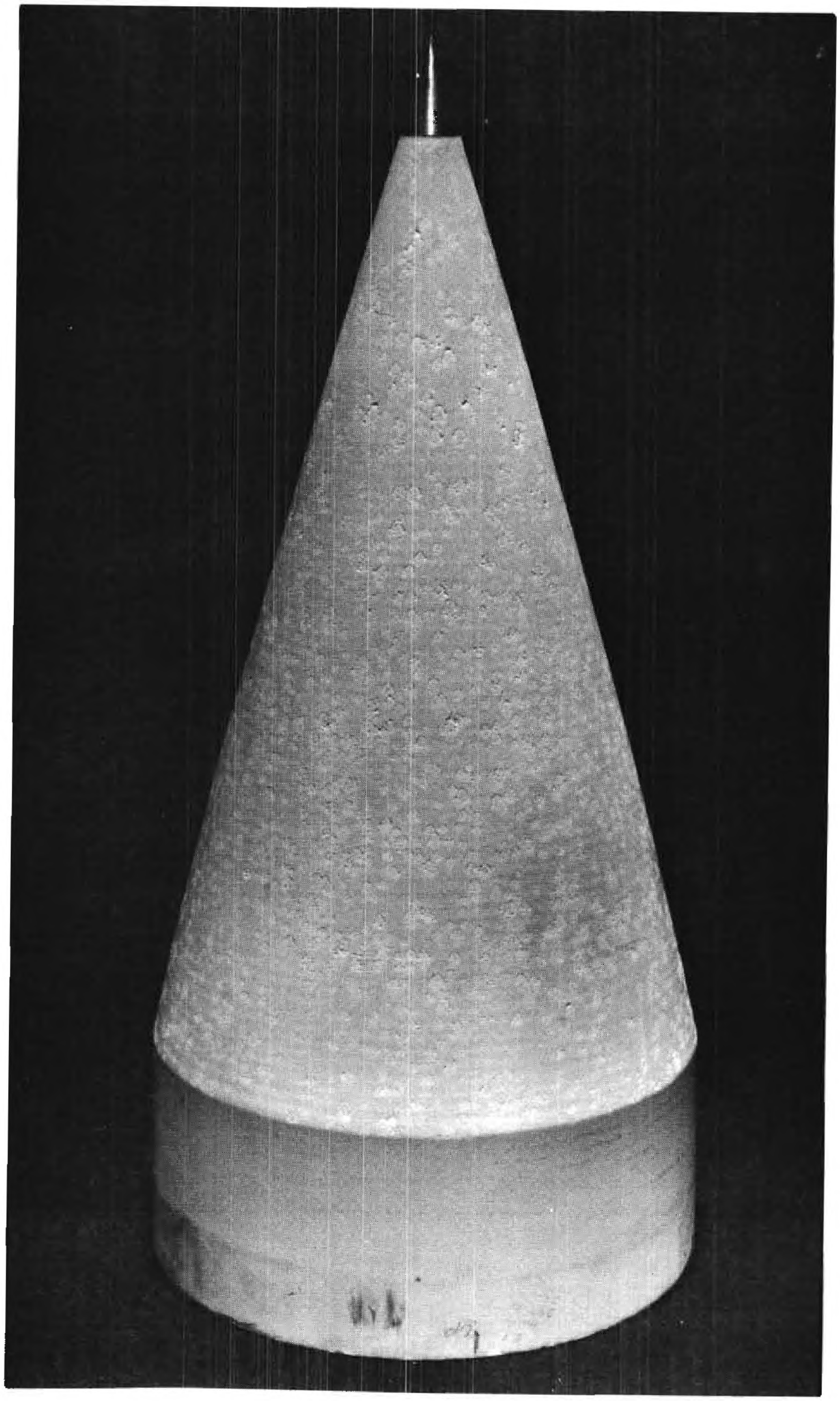

Figure 13. Side View of Radome from Run No. 2 (7RB1).

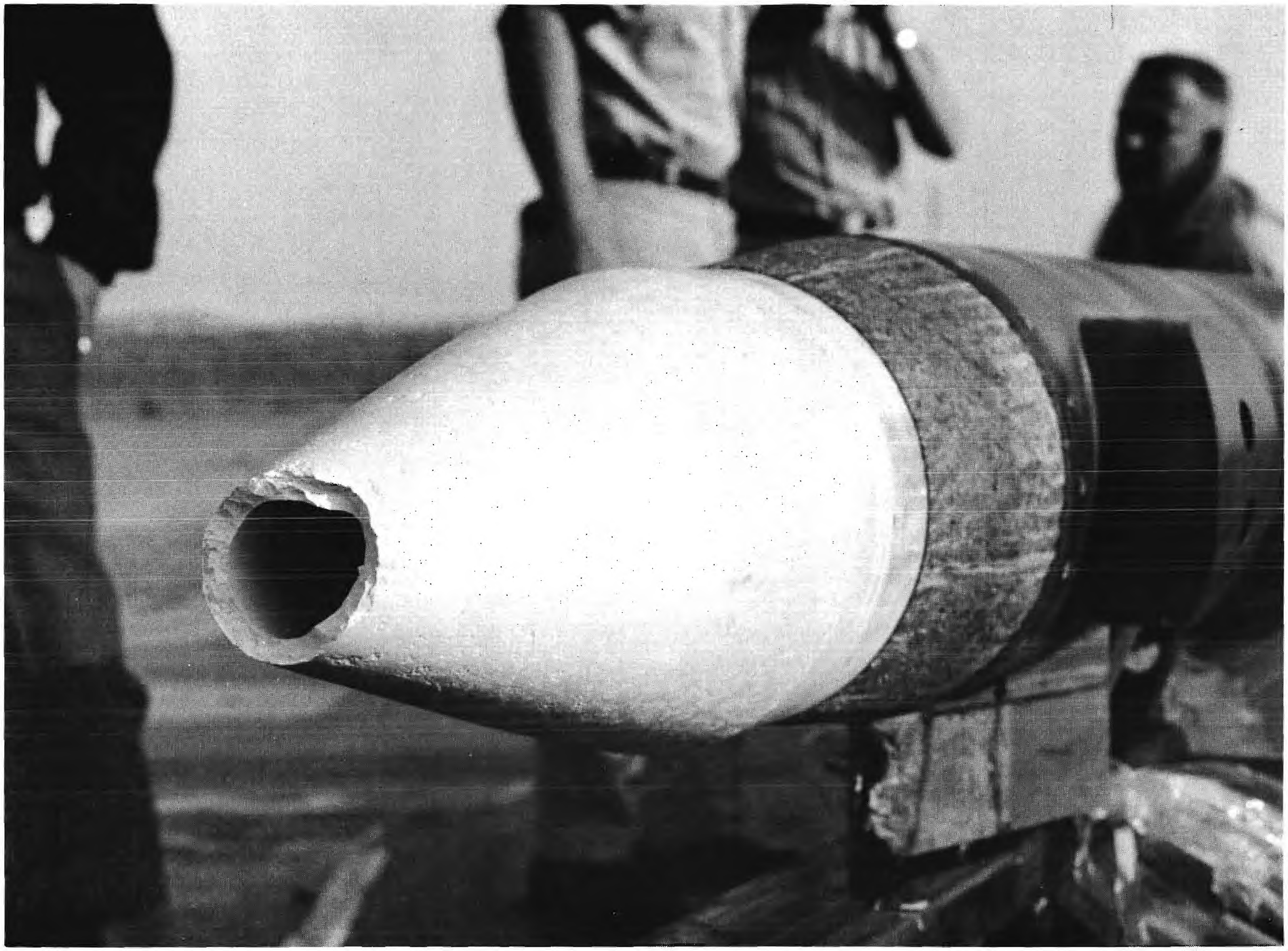

Figure 14. Radome on Sled after 800 Feet of Rain in Run No. 3 (7RC1).

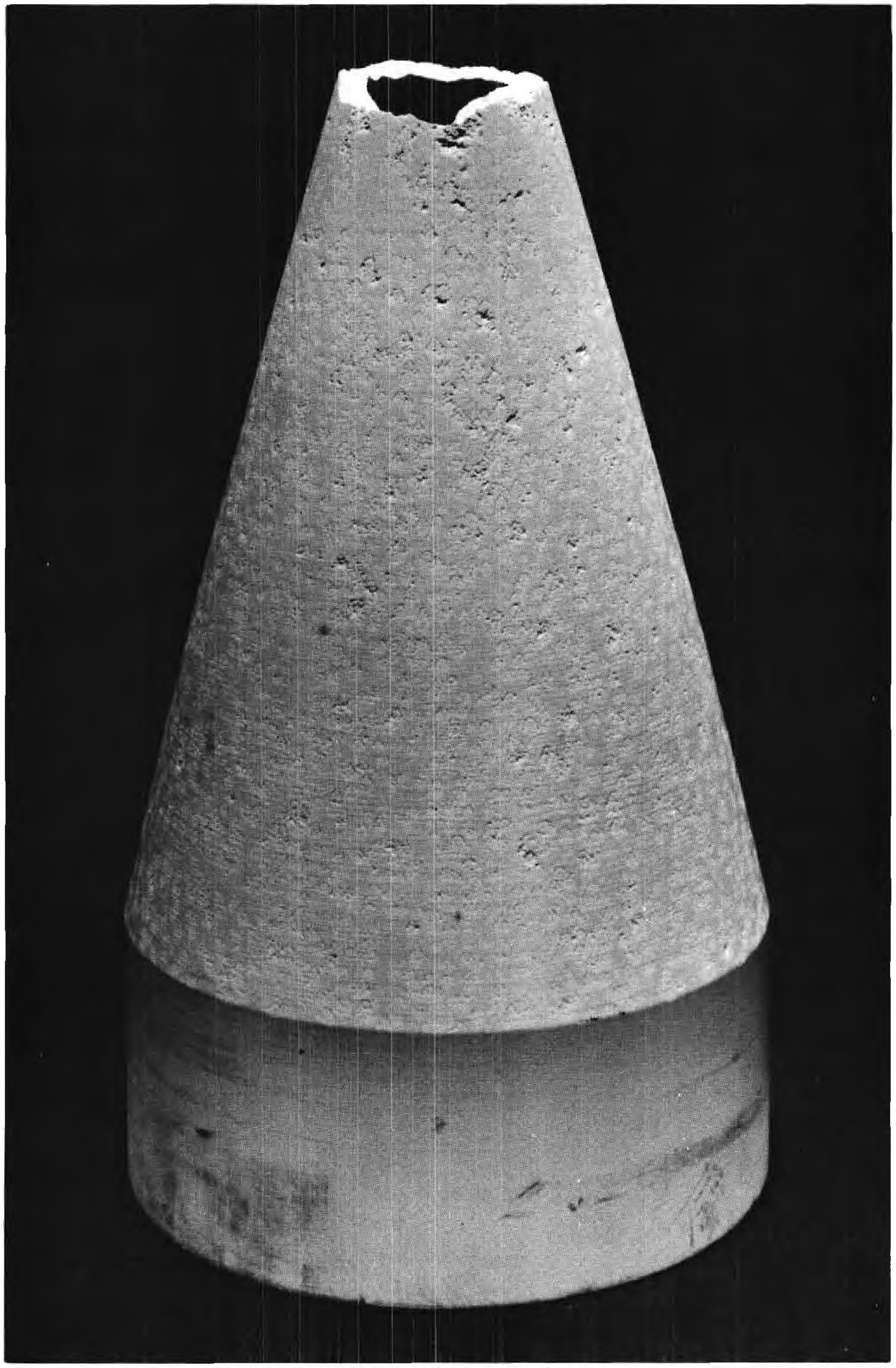

Figure 15. Side View of Radome from Run No. 3 (7RC1).

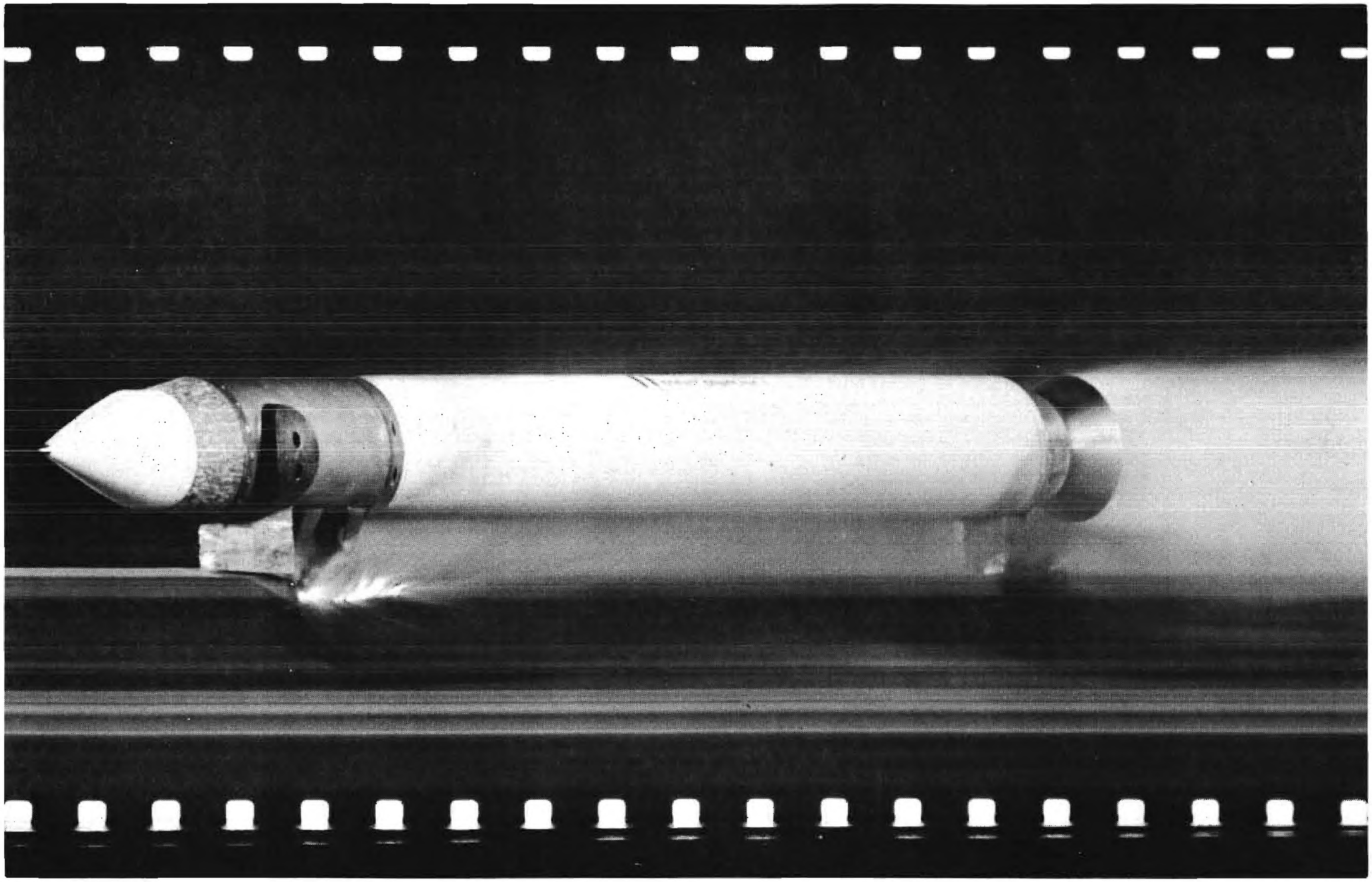

Figure 16. Image Motion Camera Photograph of Sled after Leaving 800 Foot Rain Field in Run No. 3 (7RC1).

D. Run No. 4 (7RD1)

Figures 17 and 18 show radome No. 3430 after exposure to 2000 feet of rain. A cross wind from the East of about 3 knots provided an estimated rain rate of 3.6 inches per hour. Although there was evidence of some erosion over the entire surface, it did not appear more severe than would be predicted from Runs No. 2 and 3. Also, the majority of the damage appeared on the forward 5 inches of the cone. Aft of this point the severity of the damage decreased rapidly.

E. Run No. 5 (7RE1)

Figures 19, 20, and 21 are image motion camera photographs of radome No. 1612. Figure 19 is from IMC-6 and shows the radome just before it entered the rain field. Figure 20 is from IMC-2 and shows the radome after about 1500 feet of rain. Figure 21 is from IMC-3 and shows the sled just after the radome had broken up. Figure 22 shows the attachment ring after the run. Rain damage on the attachment itself is evident on the left side of the ring where it had been peeled back due to aerodynamic forces. Figure 23 shows the location of the image motion cameras, the broken shower head and the rain field on the sled velocity vs distance curve for Run No. 5. The broken shower head confirmed the fact that the radome broke up after about 2000 feet in the rain. Figure 24 shows two portions of radome No. 1612 found near the broken shower head. The piece on the left is from the radome at a point about 6 inches from the tip of the radome. The piece on the right was located about 2 to 3 inches below the tip of the radome.

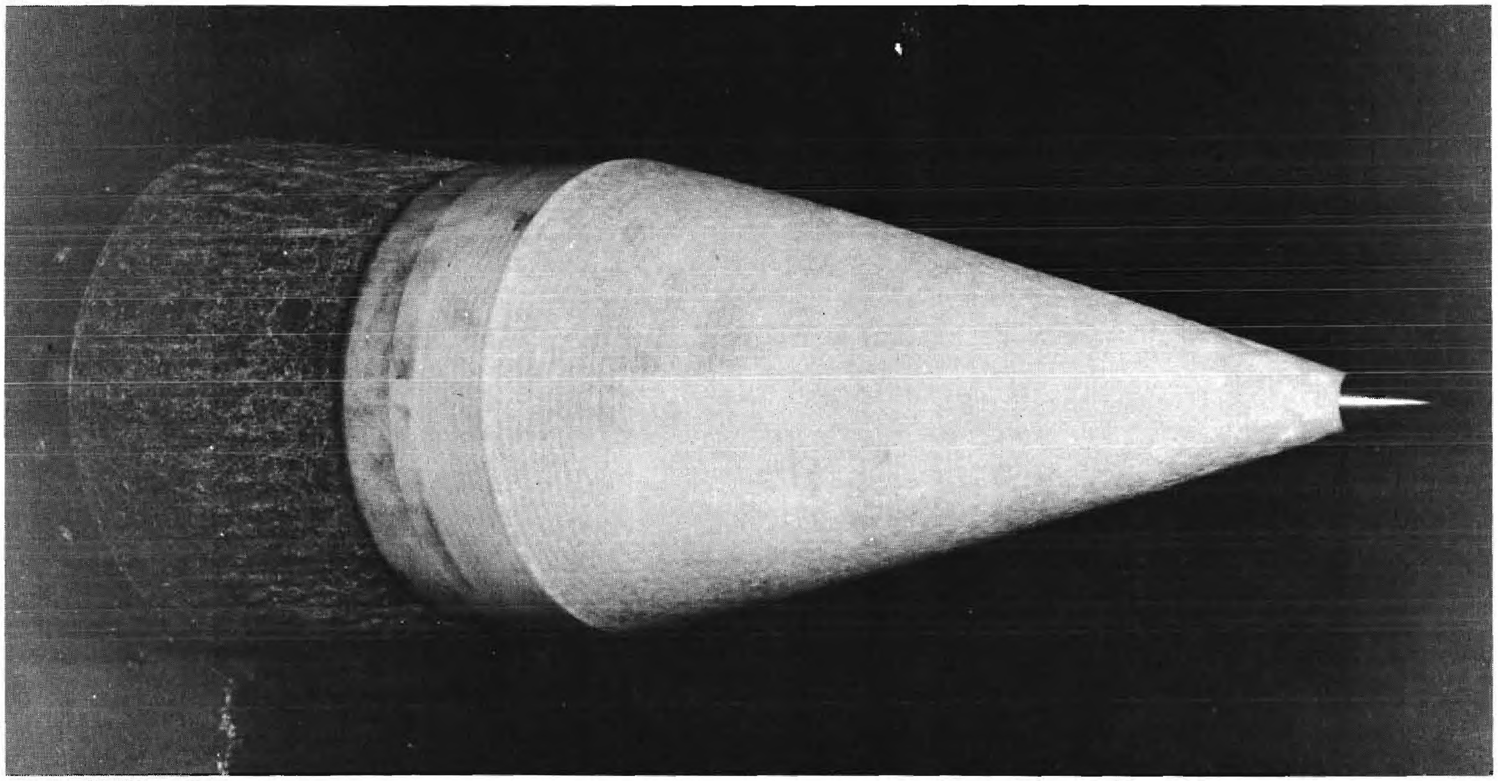

Figure 17. Radome on Sled after 2000 Feet of Rain in Run No. 4 (7RD1).

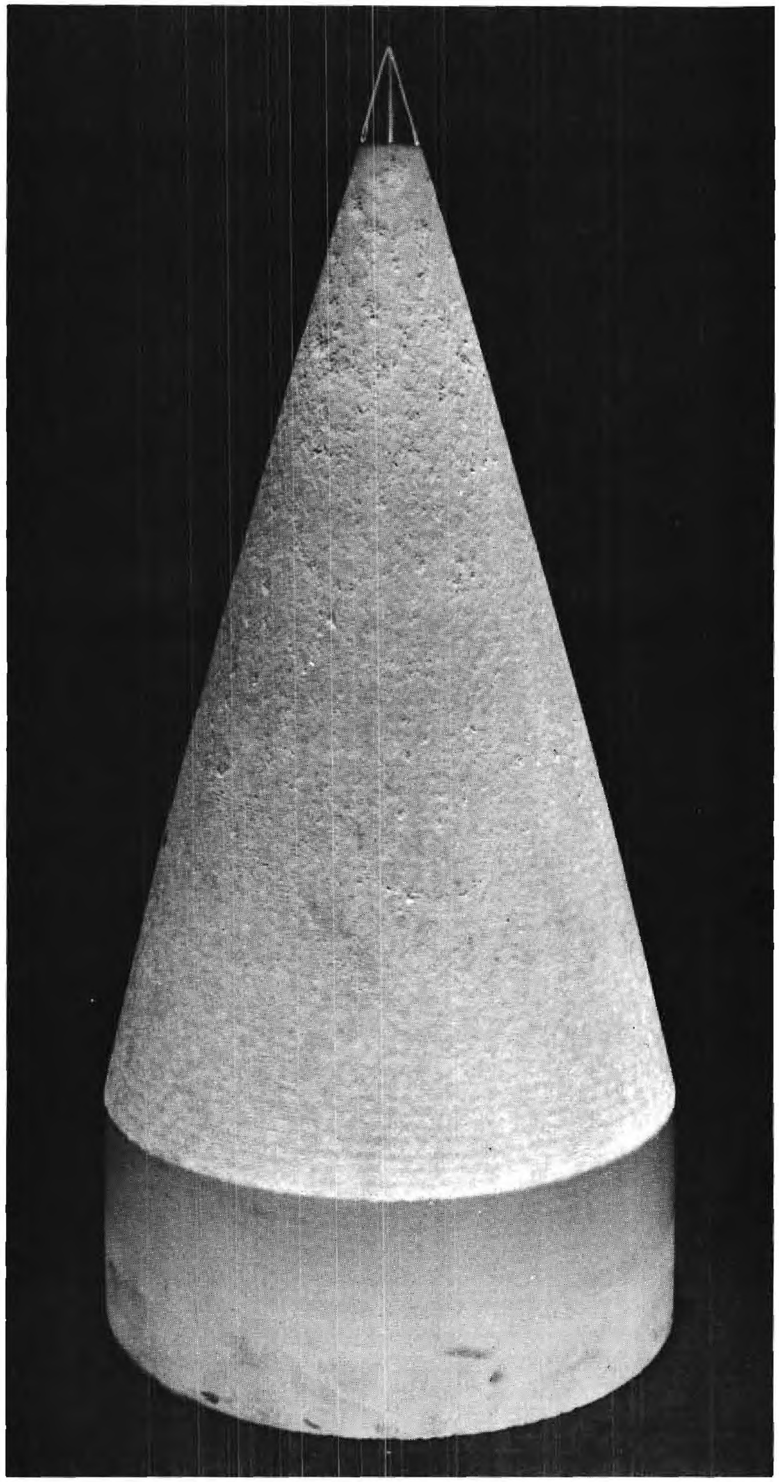

Figure 18. Side View of Radome from Run No. 4 (7RD1).

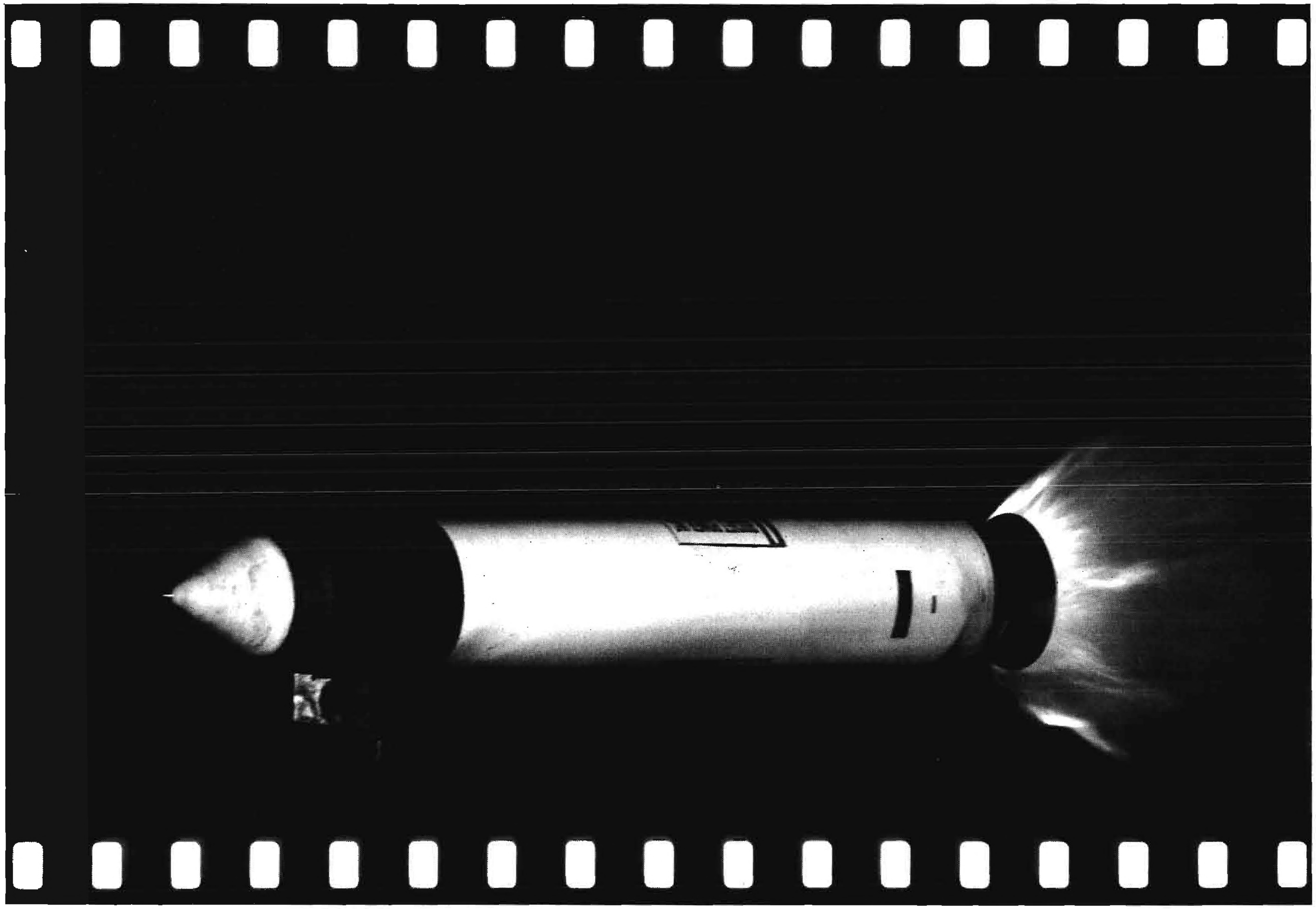

Figure 19. Image Motion Camera Photograph of Sled Entering 4000 Foot Rain Field in Run No. 5 (7RE1).

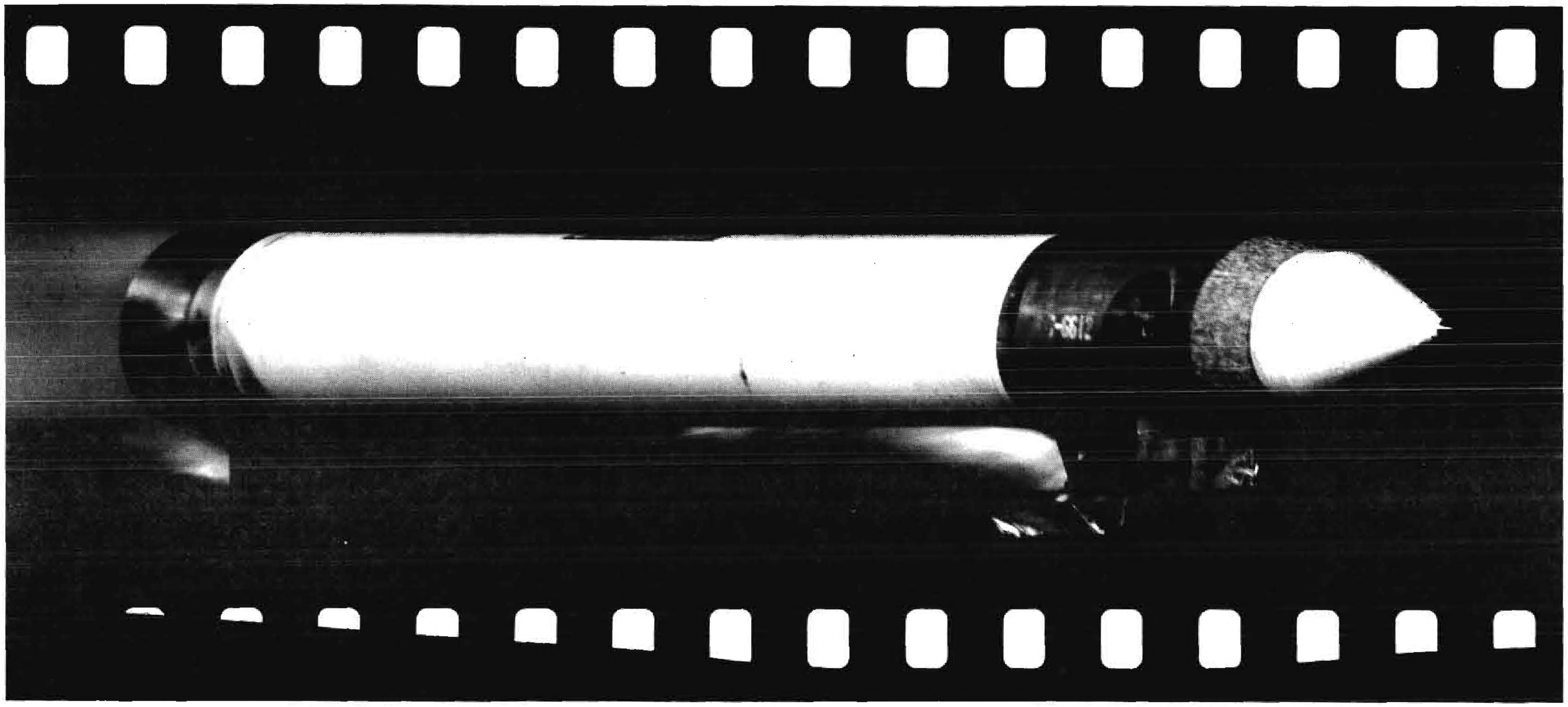

Figure 20. Image Motion Camera Photograph of Sled after about 1500 Feet in Rain Field in Run No. 5 (7RE1).

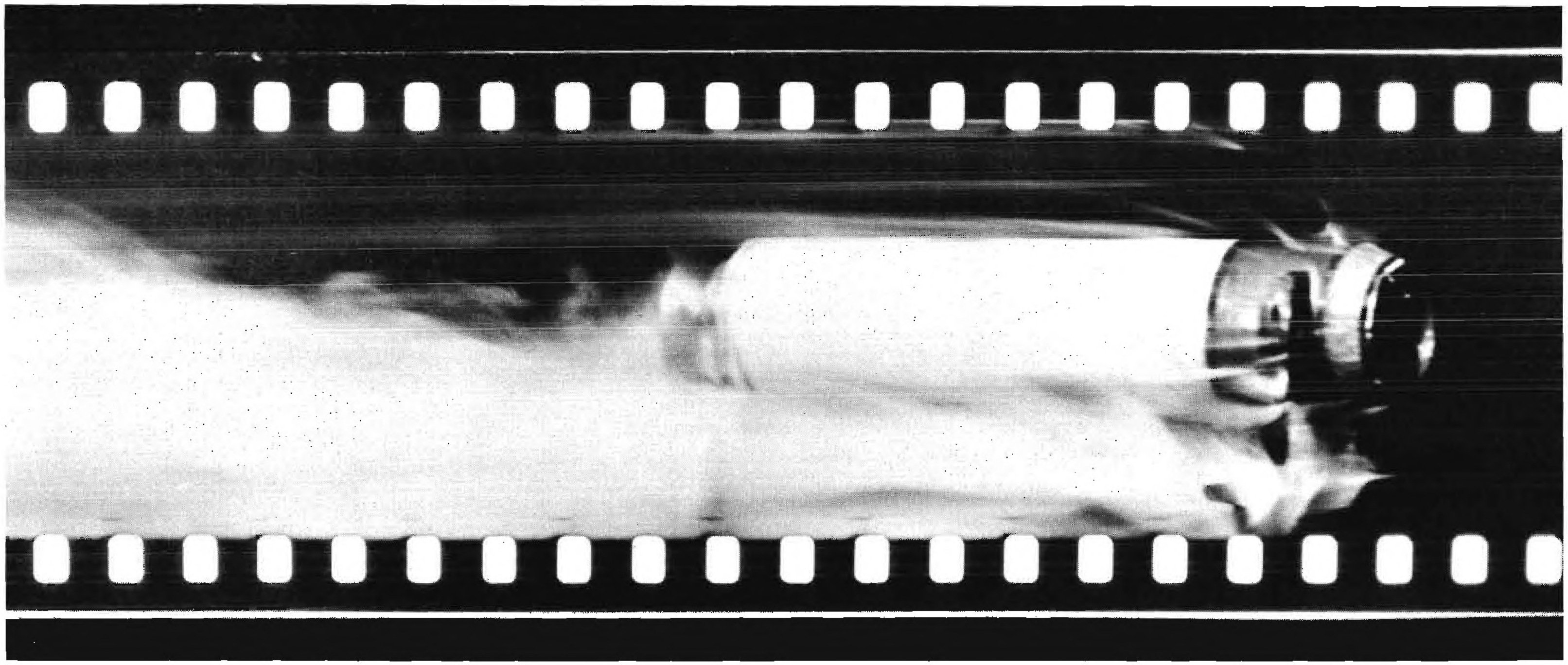

Figure 21. Image Motion Camera Photograph of Sled after about 2400 Feet in Rain Field.

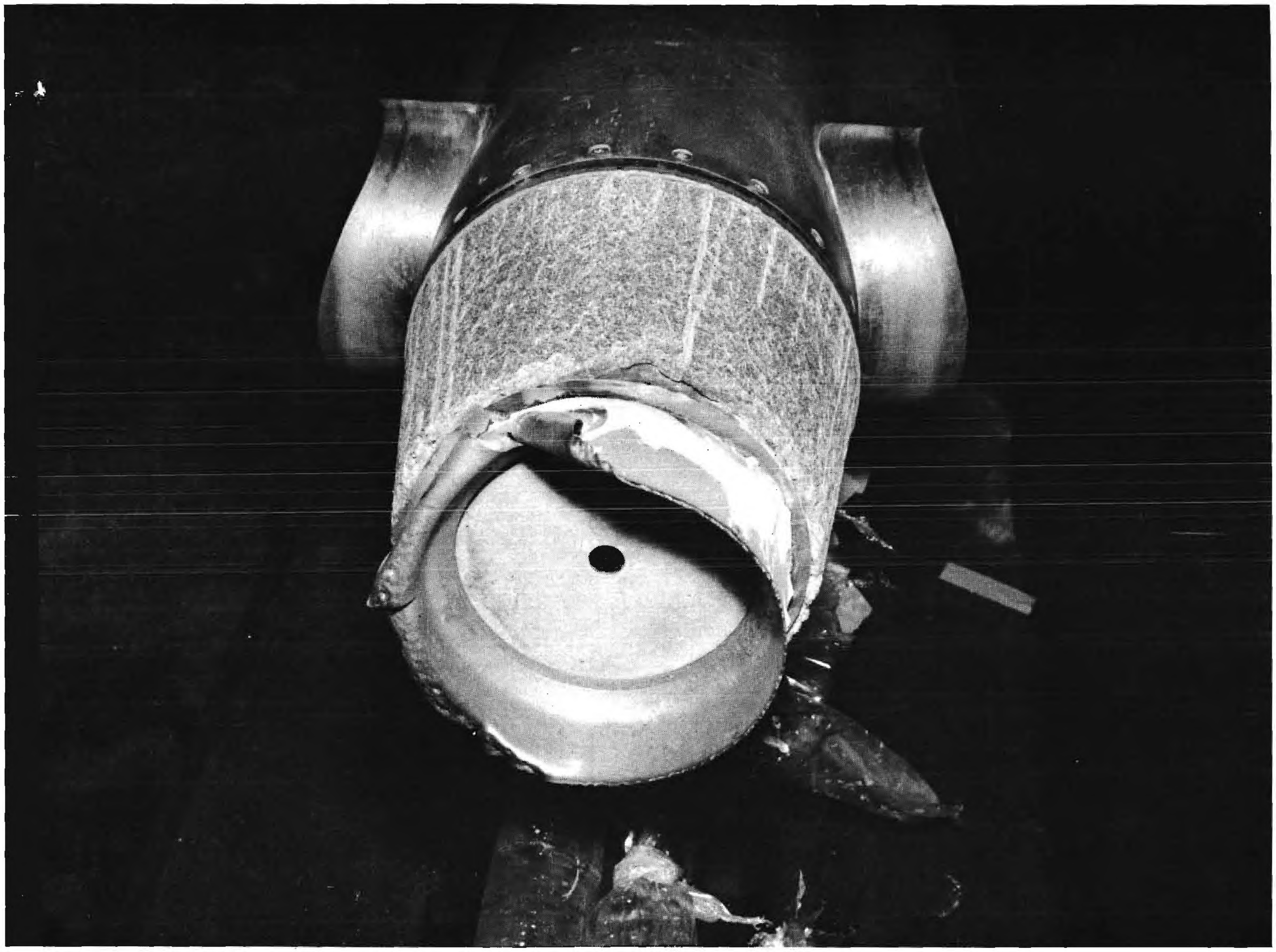

Figure 22. Attachment Ring on Sled after Run No. 5 (7RE1).

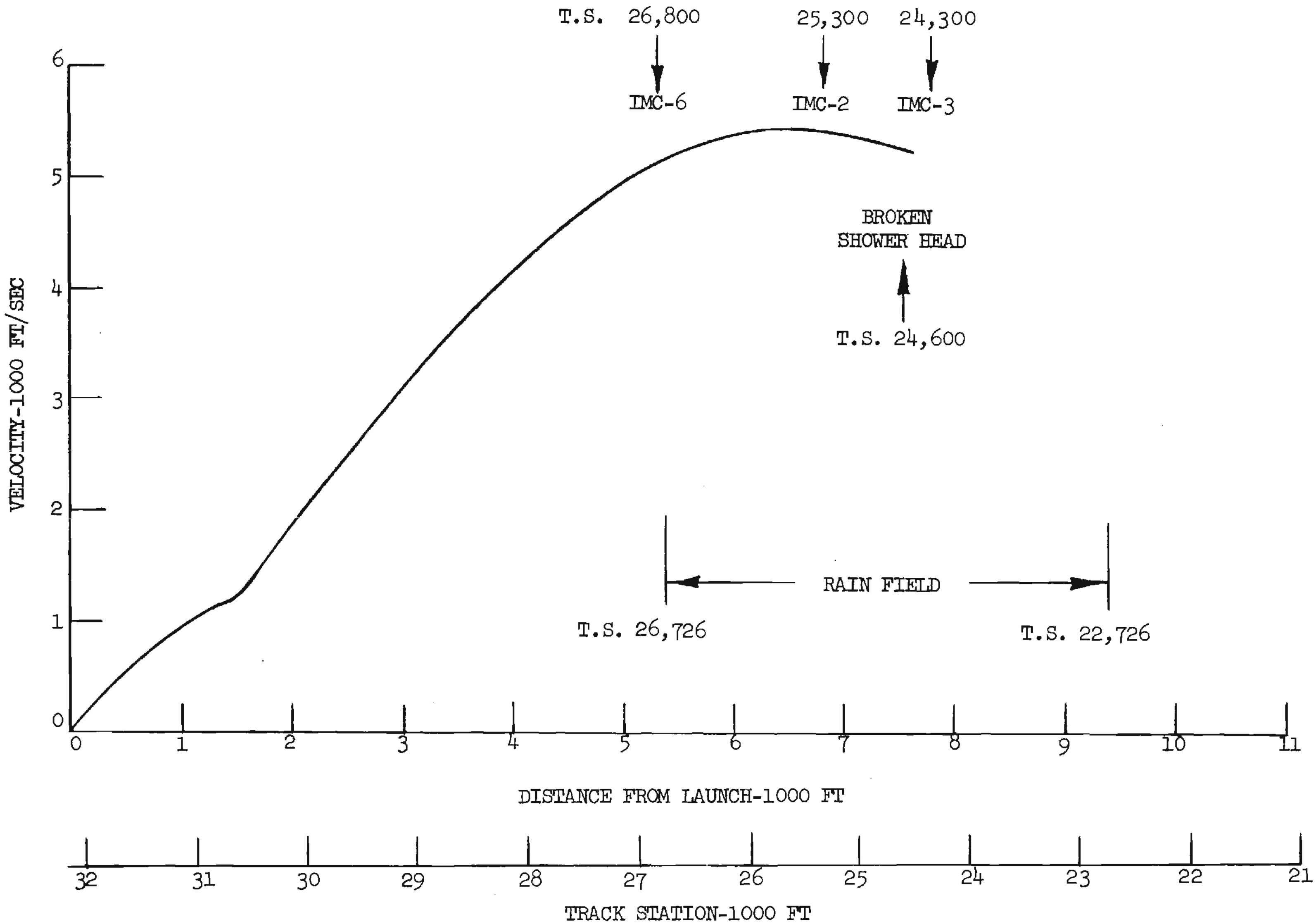

Figure 23. Sled Track Data for Run No. 5 (7RE1).

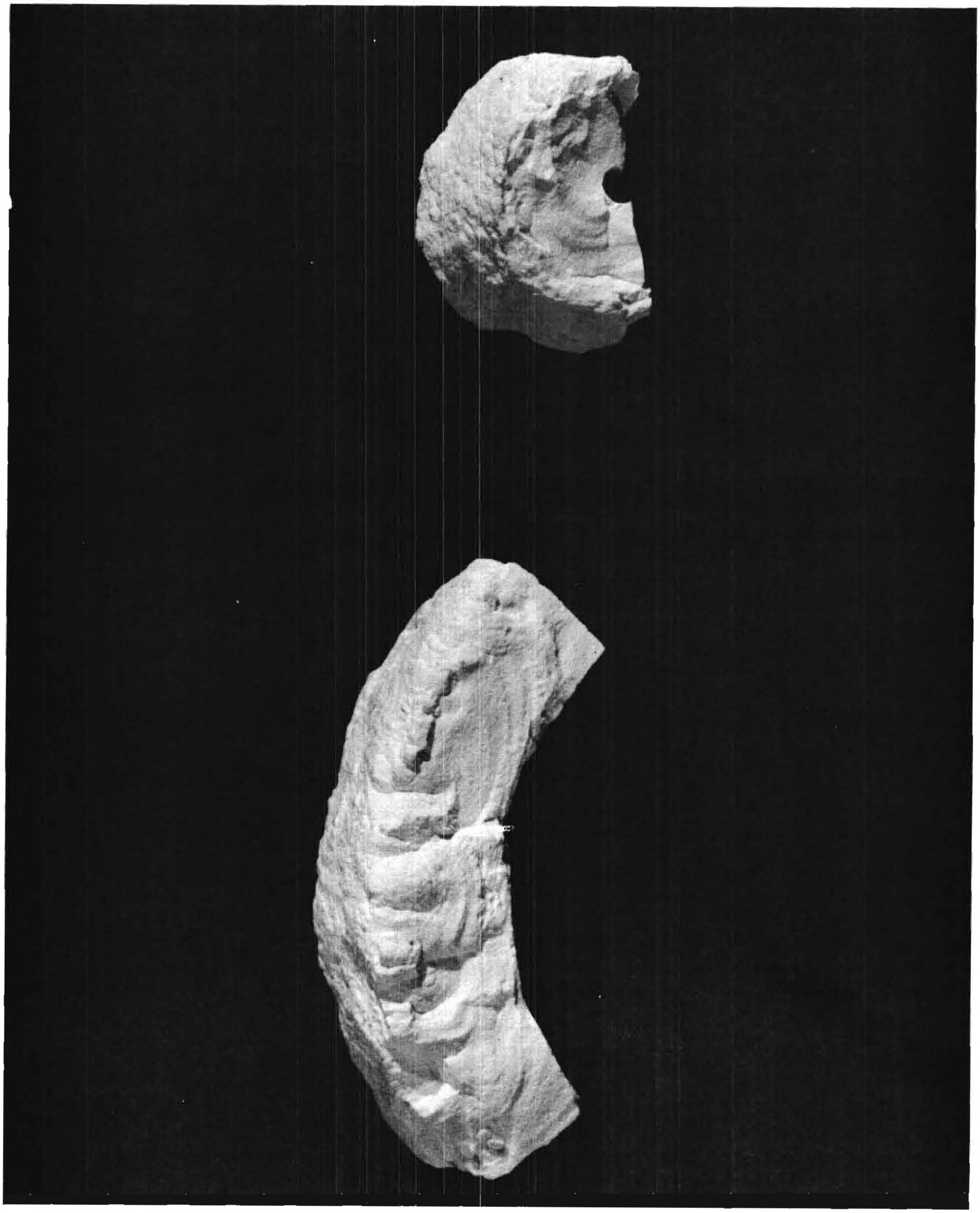

Figure 24. Broken Pieces of Radome from Run No. 5 (7RE1).

F. Run No. 6 (7RE2A)

Radome 3327 performed very much like 1612 from Run No. 5 except that it survived about 3000 feet of rain before breaking up. Figure 25 shows the location of image motion cameras, punctures in shower pipe and the rain field on the sled velocity vs distance curve for Run No. 6. Image motion camera 3 showed the radome on the sled, IMC-4 showed no radome on the sled.

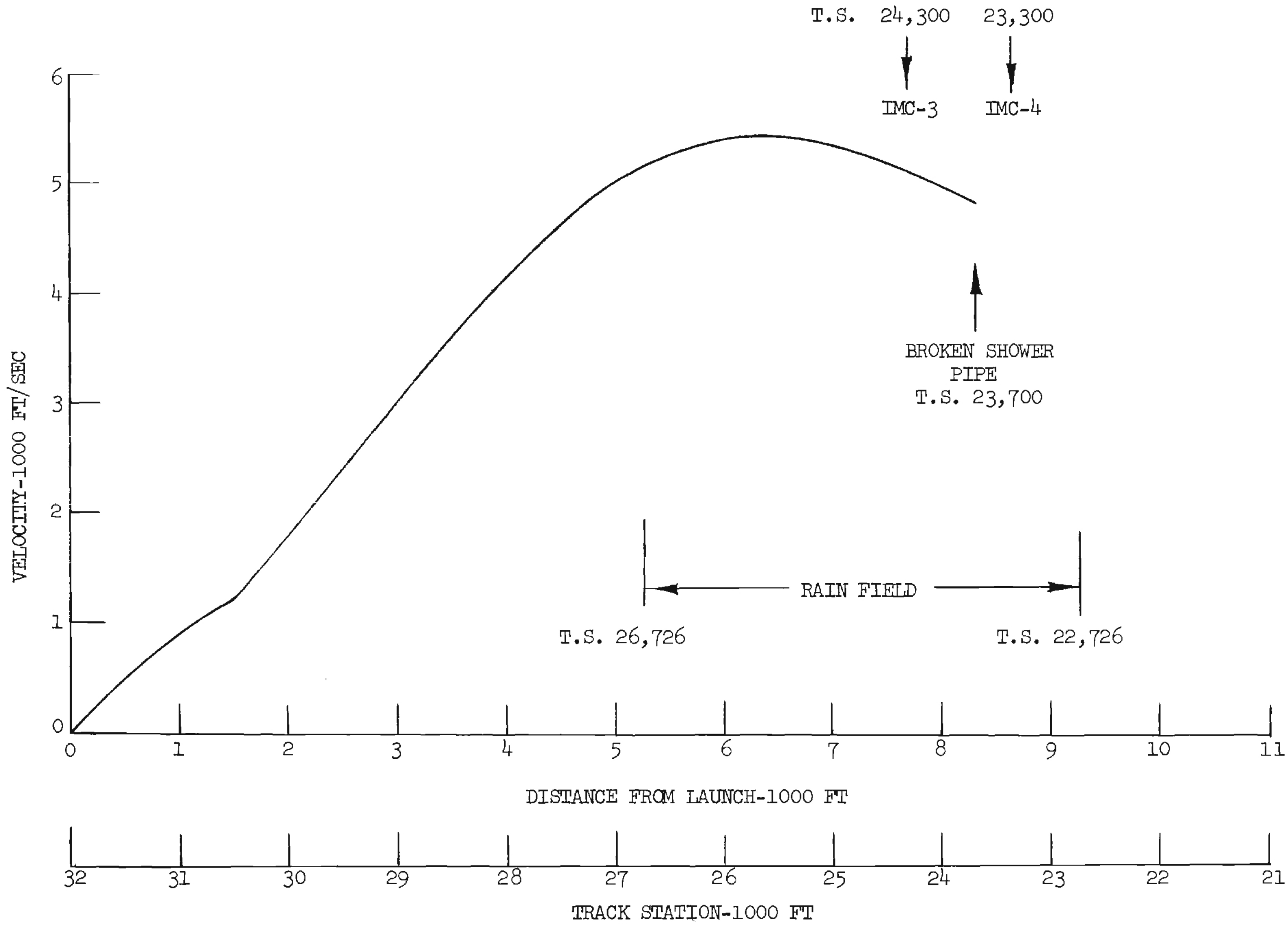

Figure 25. Sled Track Data for Run No. 6 (7RE2A).

VII. DISCUSSION OF RESULTS

A. Run No. 1 (7RA2A)

From Run No. 1 it was determined that the slip-cast fused silica radome could survive the sled environment. Although the lateral and vertical accelerations are not known, it would be expected that, at these high velocities, they would be much higher than would be expected in an actual missile flight. The normal, or axial acceleration is known to be of the order of 150 g's. As shown in Figure 4, this provided a velocity of 5600 feet per second, 4 seconds after launch. Also, it would be expected that the radome would be subjected to rather high vertical accelerations as the drag brakes were activated to decelerate the sled, after reaching peak velocity. The axial deceleration of the sled is of the order of 50 g's.

B. Run No. 2 (7RB1)

The rain damage exhibited by the radome from Run No. 2 (400 feet of rain) suggested that rain erosion should not be a serious problem. Although each drop appeared to cause some surface damage it did not appear to extend significantly beneath the glazed surface. However, from work carried out in developing the shotgun test to simulate Mach 5 rain erosion 4/ it was observed that once the impact pressure was sufficient to cause damage in the flame glazed surface, the damage to the flame glazed surface was more severe than to the unglazed surface. This appeared to be due to the fact that the damage in the glazed surface extended through the glaze with a tendency to chip out a portion of the glaze extending beyond the actual area of impact. In the unglazed surface the damage area was restricted to the area of impact. From this first run in the rain it was felt that better performance would probably have been obtained with an unglazed radome.

C. Run No. 3 (7RC1)

The surface damage caused by the 800 foot rain field in Run No. 3 was as expected from the 400 foot run. It was first assumed that the tip of the radome was lost in the rain or just as the radome emerged from the rain. This would be at the time of maximum vibration. From Figure 16 it was noted that the radome was still in one piece after leaving the rain field, and had therefore, survived the vibration associated with the peak velocity. The next point of high acceleration would be upon sled impact with the water brake. A search of this area uncovered the tip about 800 feet from the point of water brake impact. This suggested that the tip of the radome was essentially pulled away from the rest of the radome. Examination of the radome revealed that the wall thickness in the area of failure was between 0.305 and 0.350 inch. This was only one-half the thickness of the radome just 4 inches aft of this area. For some unexplained reason the wall thickness tapered uniformily from about 0.600 inches at a point about 9 inches from the base of the radome to about 0.300 inches at a point 13 inches from the base. After determining these facts, it was surprising that the radome survived the vibration associated with the peak velocity and the accompanying rain impact. One further observation was made at the track. The slippers on the sled for this run were exceptionally tight. It was only with a great deal of effort that the track crew was able to get the sled on the track. If this tight fit reduced the sled vibration it might explain why the radome survived the maximum velocity through the rain.

D. Run No. 4 (7RD1)

Run No. 4 provided very encouraging data. First, the rain rate was about 3.6 inches per hour. This was due to a cross wind of about 3 knots. Therefore, this run was equivalent to almost 3000 feet at a rain rate of 2-1/2 inches per hour. Although the surface exhibited rather general erosion, the most severe area seemed to be restricted to the area from about 4 inches behind the metal tip to the tip itself. Boresight measurements indicated no measurable effect due to this erosion. The area of most severe erosion revealed that patches of glaze were being removed. This would suggest that further rain impact would intensify local areas of damage and weaken the radome structurally. Such localized areas of damage could act as stress risers and serve as failure sites under the mechanical stresses associated with high levels of vibration which would be expected to be a maximum in this same area.

E. Run No. 5 (7RE1)

An examination of the data from Run No. 5 indicated that the radome broke up after about 2000 feet of rain. Image motion camera photographs (Figures 19, 20, and 21) show that the point of failure occurred while the drag brakes were being activated. This would probably be near the point of maximum lateral acceleration and coincident with the maximum axial deceleration of about 50 g's. From the pieces of the radome (Figure 24) which were found in the area of the broken shower head, two observations could be made: (1) there was no glazed surface remaining on these pieces, and (2) the fracture pattern in the wall of the radome was somewhat columnar from the surface to a distance of about 0.200-inch, and conchoidal below this depth. The absence of the glaze would suggest: (1) a condition of erosion more severe than Run No. 4, (2) that the glaze was not as adherent as in the previous case, and/or (3) that exceptionally high levels of vibration removed the damaged glaze from the radome. The fracture pattern for Figure 24 would suggest that some subsurface damage had occurred.

However, it is estimated that damage was only significant with respect to the vibrational loads associated with the sled trajectory and not significant with respect to an actual missile flight situation.

F. Run No. 6 (7RE2A)

From a study of the data from Run No. 6 it was concluded that the behavior of this dome was essentially the same as Run No. 5. One point was noted about the sled before this run that was not checked before Run No. 5. That is, the slippers fit very loosely. There was at least a 0.25-inch clearance between the slipper and the track. This loose fit on the track would allow for an unusually large initial amplitude of vibration which might continue into the maximum velocity region of the trajectory.

From the vibration data supplied by General Dynamics/Pomona, it was noted that there was an amplification factor between the value for the radial acceleration measured at the base of the dome, and that measured at the tip. At a level of 40 g's input at the base, an acceleration of 283 g's was measured on the radome about 3 inches from the tip, and 625 g's on the tip. In general the vibrational level measured on the body of the radome near the tip was 7 to 14 times the value at the base, and the tip provided a value 16 to 18 times as high as the base.

VIII. CONCLUSIONS

From the data obtained for the six rain erosion sled tests described in this report, several conclusions may be drawn concerning the rain erosion resistance of these flame glazed slip-cast fused silica radomes at Mach 5.

1. Rain at velocities above 5000 feet per second does cause surface damage to flame glazed slip-cast fused silica radomes. This damage may be more than superficial, particularly in the presence of high lateral vibrations, and in areas near the tip of the radome.

2. The lateral vibration near the forward section of the radome may be 7 to 14 times the value measured at the base of the radome. Since the base of the radome extends about 6 inches beyond the forward point of the wedge of the sled, it would be expected that there would be some additional amplification between the sled vibration and that at the base of the radome.

3. Flame glazed slip-cast fused silica can survive 2000 feet of rain at a rain rate of 3.6 inches per hour (measured on the Holloman track) at velocities as high as 5100 feet per second. Converting this to 2-1/2 inches per hour of rain on the track should be equivalent to about 2900 feet. To equate this to 2-1/2 inches per hour of natural rain requires a correction for the difference in terminal velocity of the rain drops in the two environments. This is 18/13 or a factor of 1.38, and would make the distance equivalent to about 4000 feet in 2-1/2 inches per hour of natural rain.

4. The maximum lateral vibration occurs in the forward portion of the radome, coincident with the area of maximum erosion damage. Radomes which have failed in the rain have done so just after the initiation of the drag brakes. At this point a multiaxial stress situation exists. Lateral vibration is near a peak, and axial deceleration reaches a maximum of about 50 g's at this point. This undesirable mechanical situation coupled with the maximum surface erosion in the same area of the radome would suggest an abnormal stress condition, perhaps an order of magnitude more severe than would be expected in flight.

It appears therefore that in these tests, the rain damage is sufficient to weaken the material to the point where the severe mechanical environment is sufficient to destroy the radome. This is not a measure of the amount of rain necessary to defeat the radome in a real missile application. It rather suggests an absolute minimum environment in which glazed slip-cast fused silica radomes would perform satisfactorily in a real flight situation.

IX. RECOMMENDATIONS

In order to determine more realistically the rain erosion resistance of slip-cast fused silica, the following recommendations are made:

A. Recommendations for Immediate Future

1. Run sled test with unglazed slip-cast fused silica radome in 4000 feet of rain.

2. Modify sled slippers to provide as accurate and as close a fit to the track as possible.

3. Instrument sled, transition piece, and radome base to telemeter lateral acceleration data during sled run.

B. Recommendations for Future Program

1. Modify radome design to provide radome attachment directly to sled. (Eliminate transition piece.)

2. Modify tip design to minimize weight of metal tip.

3. Modify slippers to provide high temperature, high strength steel slippers with replaceable inserts, and lengthen slippers to provide greater contact area.

The carrying out of these recommendations should minimize the severity of the abnormal mechanical environment and allow for the establishment of the rain erosion resistance of slip-cast fused silica.

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13. ABSTRACT This report describes a rocket sled test program which was conducted to determine the rain erosion resistance of slip-cast fused silica at velocities above 5000 feet per second. The fabrication techniques used at the Georgia Institute of Technology to slip-cast, heat treat and flame glaze the radomes are discussed. The results of the six sled tests which were run at Holloman Air Force Base, New Mexico, and which covered distances up to 4000 feet in an artificial rain field of 2-1/2 inches per hour are presented. The failure of two radomes to survive rain damage for distances between 2000 and 4000 feet in the rain field is attributed to the severe mechanical environment which results from sled vibration. This condition is considered extremely unrealistic with respect to a missile flight situation. It is concluded that flame glazed slip-cast fused silica should survive a minimum of 4000 feet in a natural rain of 2-1/2 inches per hour under actual missile flight conditions. It is recommended that at least one additional sled test be run. The slip-cast fused silica radome should be unglazed since simulated rain erosion testing has suggested that the rain damage should be less severe for the unglazed than for the glazed radome. Also, recommendations are made concerning means for reducing the vibration provided by the rocket sled.

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A-925

FINAL TECHNICAL REPORT

PROJECT A-925

RAIN EROSION SLED TESTING OF SLIP-CAST FUSED SILICA RADOMES

By

J. N. Harris, J. D. Walton, Jr., B. E. Johnson, et al

Contract DA-01-021-AMC-14464(Z)

Prepared for

U. S. Army Missile Command

Redstone Arsenal

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Engineering Experiment Station

GEORGIA INSTITUTE OF TECHNOLOGY

Atlanta, Georgia

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GENERAL DYNAMICS/POMONA
Pomona, California

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FOREWORD

This report was prepared by the Engineering Experiment Station of the Georgia Institute of Technology, Atlanta, Georgia, under U. S. Army Contract DA-01-021-AMC-14464(Z).

Principal personnel participating in this work include: J. D. Walton, Jr. and J. N. Harris.

This report supersedes Final Technical Report, Part I, Project A-925, Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes, prepared by the Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia. This report contains all pertinent information from Part I, and includes the results from the final sled test with an unglazed slip-cast fused silica radome, which information was to have been published as Part III.

Part II of the report, covering: (a) the assembly of the metal tip and attachment to the radome, (b) the mechanical and boresight testing of the completed radome assembly, and (c) boresight testing of the radomes after the sled tests, was prepared under sub-contract by the Radome Engineering Group, General Dynamics, Pomona Division, Pomona, California, and is included, as submitted by General Dynamics/Pomona, as an appendix to this report.

Principal General Dynamics/Pomona personnel participating in this work include: B. E. Johnson, L. H. Lightfoot, and J. B. Samonte.

ABSTRACT

This report describes a rocket sled test program which was conducted to determine the rain erosion resistance of slip-cast fused silica at velocities above 5000 feet per second. The fabrication techniques used at the Georgia Institute of Technology to slip-cast, heat treat and flame glaze the radomes are discussed. The results of the seven sled tests which were run at Holloman Air Force Base, New Mexico, and which covered distances up to 4000 feet in an artificial rain field of 2-1/2 inches per hour are presented. The failure of two radomes to survive rain damage for distances between 2000 and 4000 feet in the rain field is attributed to the severe mechanical environment which results from sled vibration. This condition is considered extremely unrealistic with respect to a missile flight situation. Rain erosion damage at Mach 5 is less severe on unglazed slip-cast fused silica radomes than on flame glazed slip-cast fused silica radomes. It is concluded that flame glazed or unglazed slip-cast fused silica should survive a minimum of 4000 feet in a natural rain of 2-1/2 inches per hour under actual missile flight conditions.

Recommendations are made concerning means for reducing the vibration provided by the rocket sled.

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I. PURPOSE

The purpose of Contract DA-01-021-AMC-14464(Z) is to study the behavior of slip-cast fused silica radomes operating in a rain environment at velocities near Mach 5.

II. BACKGROUND

One of the most perplexing problems associated with high speed missile flight is rain erosion. It has been investigated generally for over twenty years and the mechanism of rain damage has been studied specifically for over a decade. Nevertheless, the problem remains unsolved. Also, little hope is voiced that a solution will be found in the near future that will quantitatively relate the properties of a material to its response to supersonic rain impact. A recent report by Wahl reviews the current state of the art 1/.

Slip-cast fused silica has been considered recently for several hypersonic missile radome applications. It is unique among current radome materials in that it combines excellent thermal shock resistance with excellent electrical properties, ease of fabrication, low thermal conductivity, and low cost. The properties of slip-cast fused silica suggest that it should perform thermally and electrically up to Mach 6 or 7 at low altitude. Performance at higher speeds would be limited only by the ablation and the electromagnetic signal attenuation. Therefore, slip-cast fused silica has the potential of functioning as a radome over the range of environments extending from supersonic missiles to reentry bodies. Only one property of this material remains to be established over this wide range of velocities, and that is its rain erosion resistance.

Early in 1963 slip-cast fused silica radomes were evaluated for rain erosion resistance on the SNORT rocket sled track at the Naval Ordnance Test Station, China Lake, California 2/. These tests indicated that pointed fused silica radomes were satisfactory at velocities up to Mach 2.7 (maximum velocity of test). The artificial rainfall for these tests contained an average drop size of 2.0 millimeters with a rate of 2 inches per hour. The length of the rain field was 2500 ft.

III. INTRODUCTION

This program was undertaken to determine the rain erosion resistance of slip-cast fused silica at Mach 5. The rocket sled track at Holloman Air Force Base, New Mexico was selected as the site for the tests. The two stage sled was designed and constructed by Inca Engineering Corporation, San Gabriel, California. The radomes were fabricated and glazed at the Georgia Institute of Technology, Atlanta, Georgia. General Dynamics/Pomona Division provided the metal tip and attachment system and conducted electrical and mechanical tests on the finished radomes. Georgia Tech was responsible for monitoring all tests and documenting the test results.

IV. TEST PROGRAM

A. The Radome

Figure 1 shows the radome configuration that was selected. This test shape provides the front 13 inches of an ogival radome approximately 31 inches long and 13-3/4 inches in base diameter. The entire radome could not be used because of the weight restrictions imposed by the sled design. However, it was decided that the rain damage would be most severe on the front 1/3 of the radome and that this frontal area could be provided by the smaller radome.

From Mach 2.7 rain erosion tests run at NOTS 2/ it was decided that a metal tip would be used at the stagnation point. This would eliminate any raindrop impingement normal to the radome surface. It was also decided that the surface of the radome would be flame glazed since flame glazed slip-cast fused silica radomes had provided more resistance to rain erosion damage than the unglazed radomes. Run No. 7 was made with an unglazed radome since shotgun screening tests at Georgia Tech indicated possible better performance at Mach 5 for unglazed silica.

The attachment and tip design, as provided by General Dynamics/Pomona, is shown in Figure 2.

B. The Rocket Sled

The two stage rocket sled is shown in Figure 3. The first stage is a Cajun rocket motor and the second stage is a Gila IV motor. The first stage accelerates the vehicle to about 1200 feet per second, at which point the second stage ignites and accelerates the sled to a design velocity of about 5600 feet per second. The typical sled velocity is shown as a function of time and distance from launch in Figure 4. The sled and radome are shown in Figure 5.

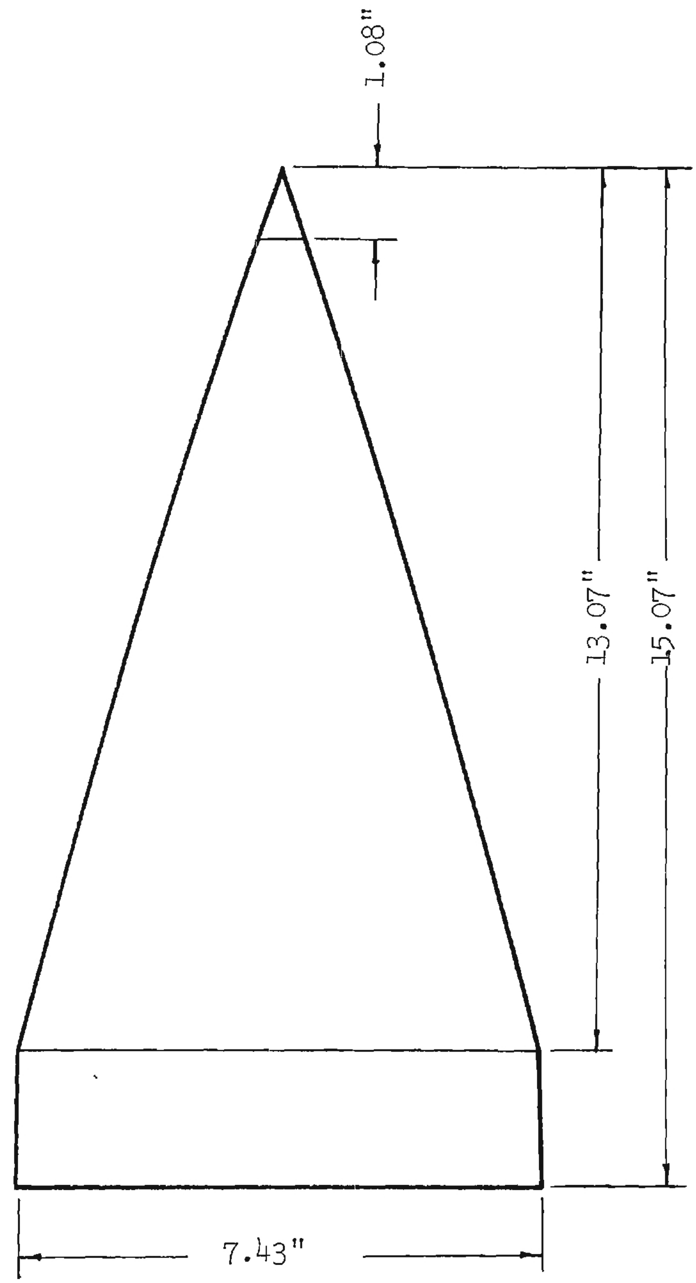

Figure 1. Radome Configuration for Mach 5 Rain Erosion Sled Tests.

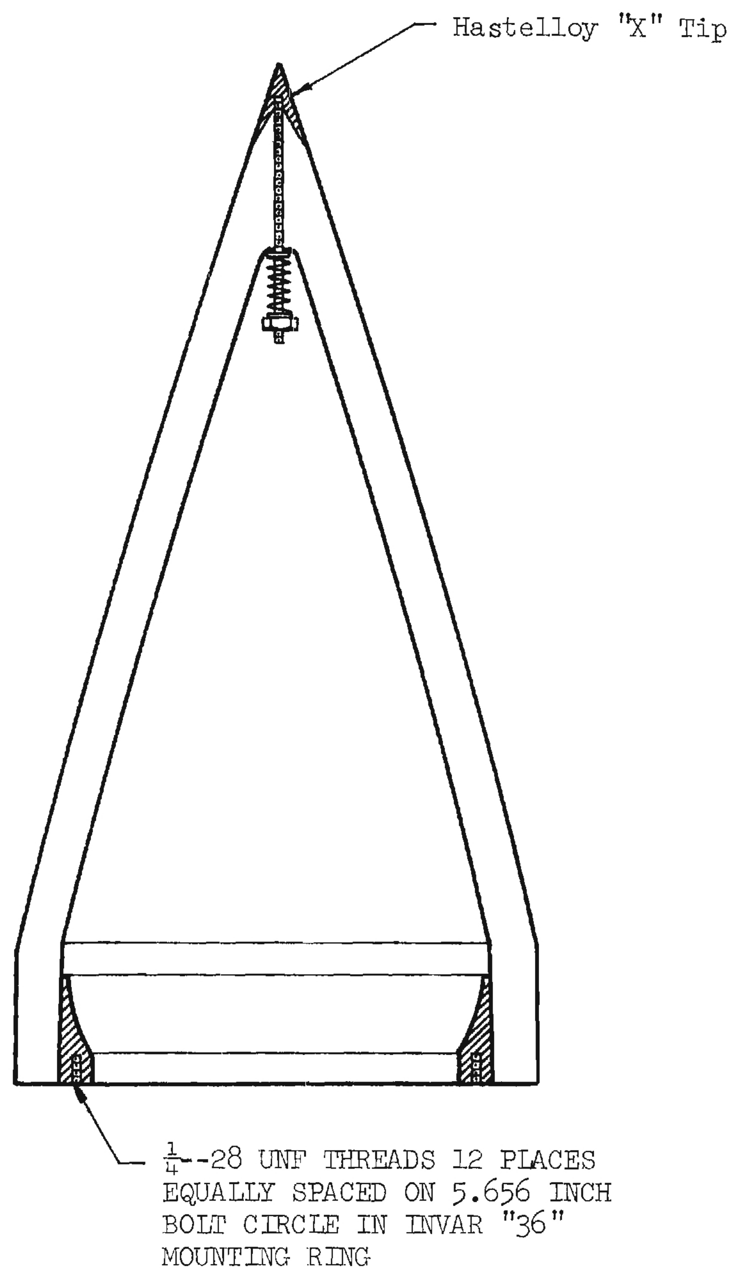

Figure 2. Radome Assembly Showing Tip and Attachment Design.

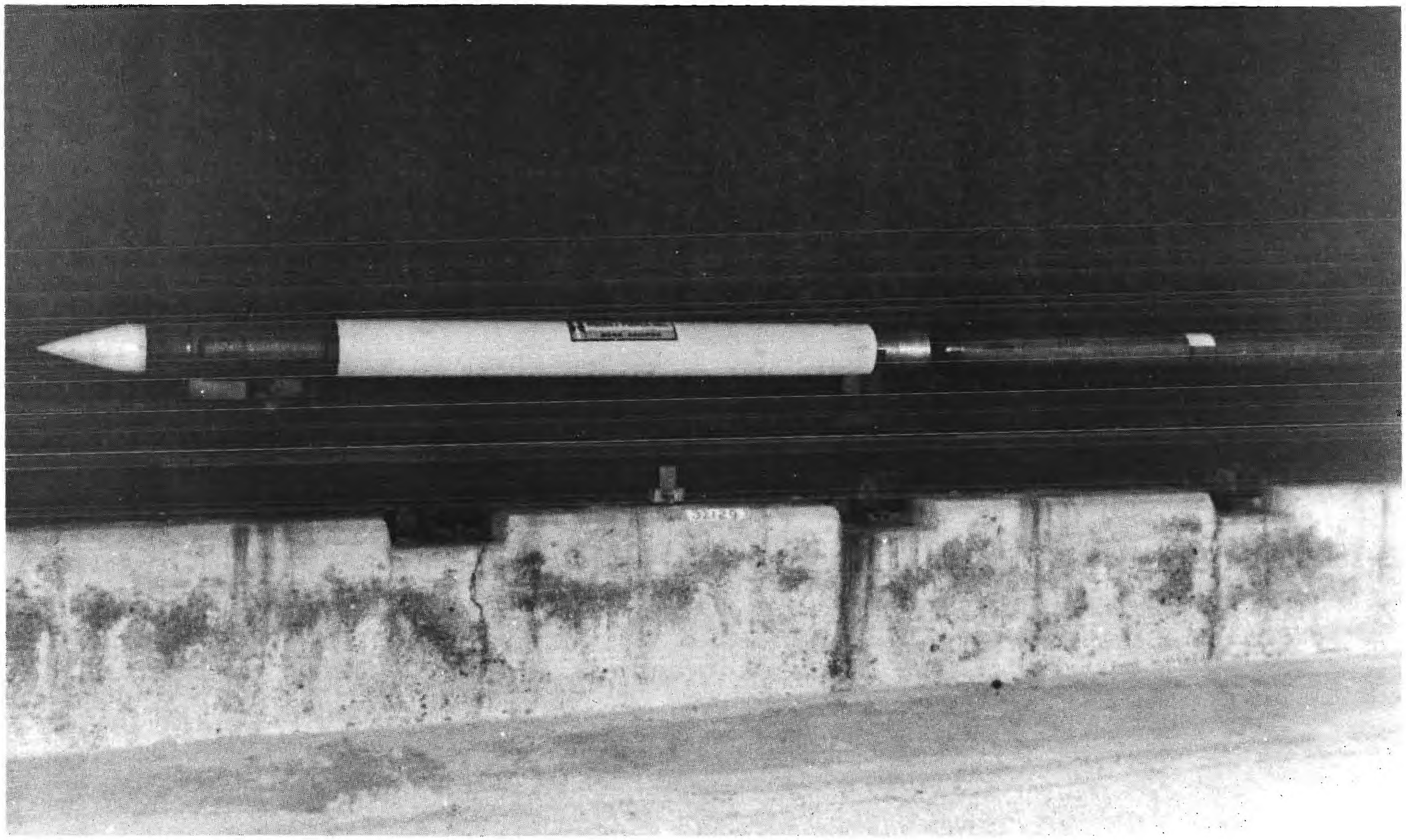

Figure 3. Two Stage Rocket Sled Used in Mach 5 Rain Erosion Sled Tests.

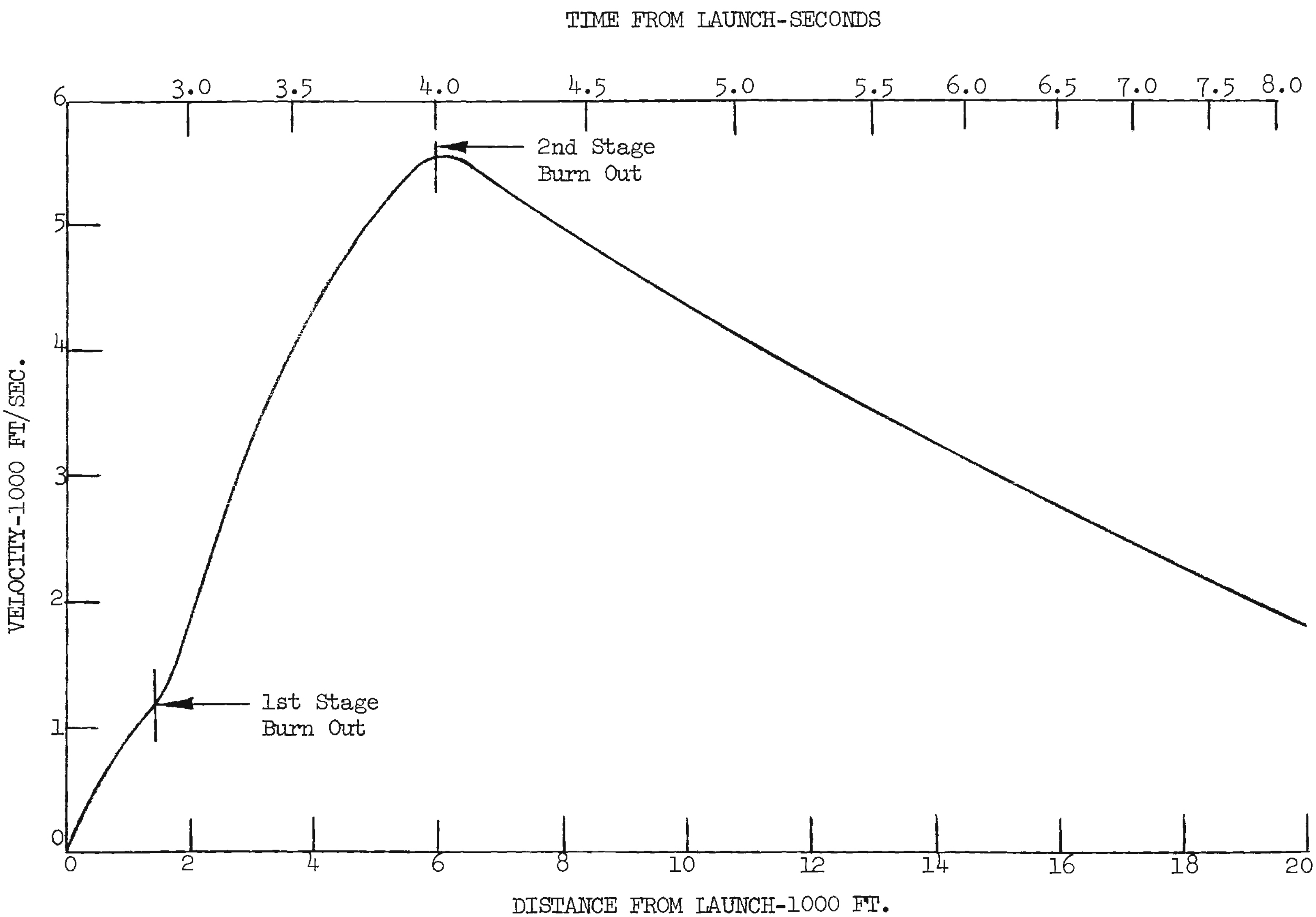

Figure 4. Typical Sled Velocity vs Distance and Time from Launch.

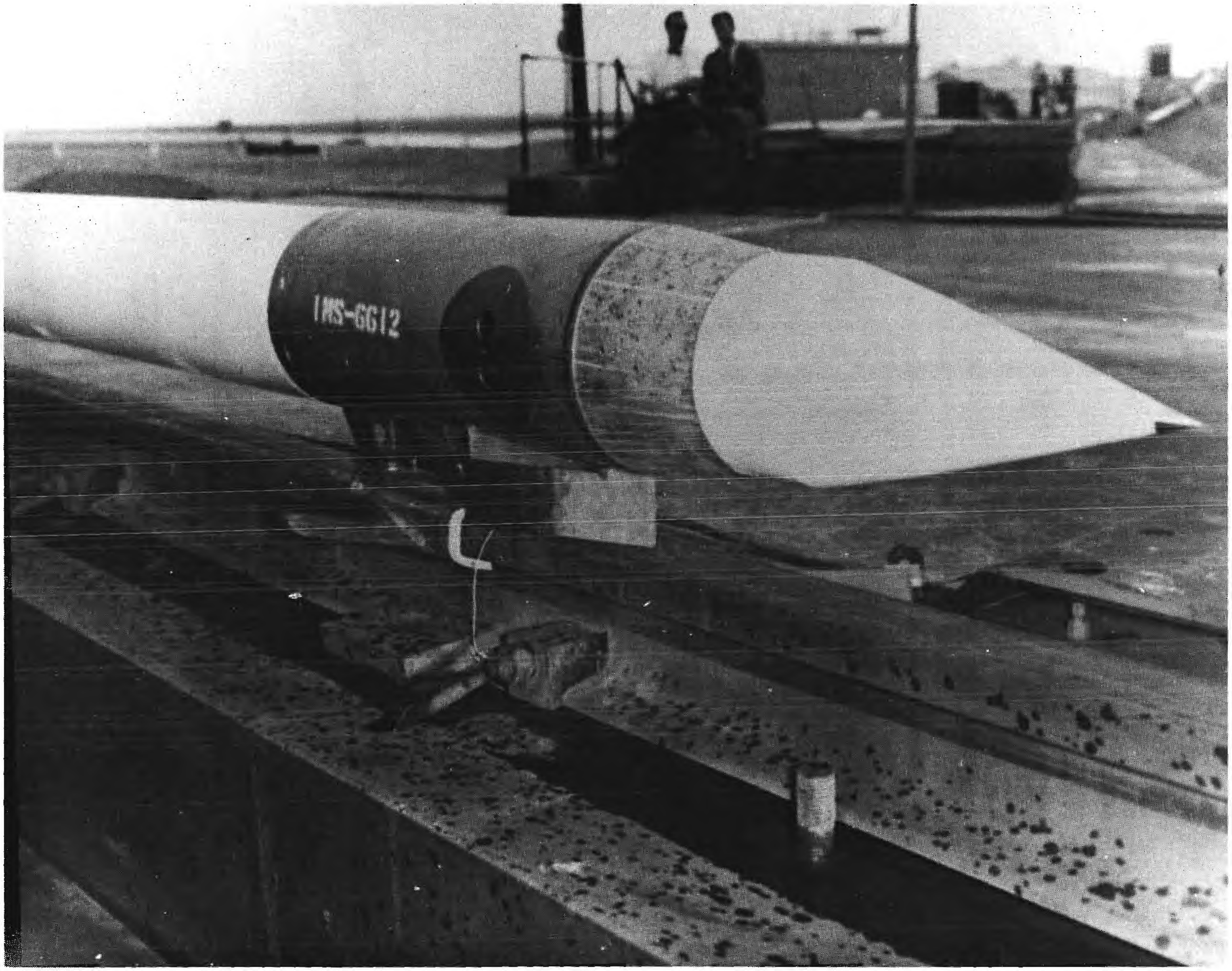

Figure 5. Close-up of Sled on the Track Showing Radome and Transition Piece.

C. The Test Track Facility

The Holloman facility provides 35,000 feet of test track with a rain field of 6000 feet. The rain section is located so that there are 8000 feet of track for acceleration of the vehicle and 21,000 feet for deceleration. The simulated rain is supplied by spraying sections 400 feet long. Each section contains 50 spray heads spaced 8 feet apart. The length of the rain field can be adjusted to provide any whole multiple of 400 feet 3/.

D. The Test Environment

The tests were designed so that the peak velocity would be obtained in the rain field. The rain rate was adjusted to be 2-1/2 inches per hour with no wind blowing. The average drop size was between 1.5 and 2 millimeters. The programed rain environment of each sled run is given in Table I.

TABLE I

RAIN ENVIRONMENT SCHEDULE FOR SLED TESTS

Run No.	Holloman Number	Rain Field	Date Run
1	7RA2A	None	June 27
2	7RB1	400	June 30
3	7RC1	800	June 30
4	7RD1	2000	July 1
5	7RE1	4000	August 11
6	7RE2A	4000	September 21
7	7RF2	2000	December 20

V. EXPERIMENTAL WORK

A. Fabrication of Test Radomes

The test radomes were slip-cast from a fused silica slip purchased from Glasrock Products, Incorporated. The slip-casting was carried out in plaster molds using pressure casting techniques.

1. Mandrel Modification

An existing tangent ogive aluminum mandrel, approximately 31 inches high with a base diameter of 13 inches, was available for this work. The mandrel was constructed under a Navy contract and was modified, with Navy approval, to provide the desired radome shape for the sled tests.

This mandrel was separated into two sections at a point where the base diameter of the front ogival section was 7.447 inches. Three circular aluminum sections two inches in thickness and one section one inch in thickness were pinned together and attached to the existing front section of the radome to form a base extension for the necessary attachment. This extension section was machined to mate with the base of the radome in the shape of a cone-frustum having a one degree taper.

2. Mold Fabrication

The necessary molds were fabricated using U. S. Gypsum Pottery Plaster No. 1. All molds were made with 91.6 pounds of water and 114.4 pounds of plaster. In all cases, slaking time was 4 minutes and mixing time was 5 minutes. Water was allowed to remain in the mixing tank sufficiently ahead of mixing time for the water to come to room temperature before adding the plaster. All molds were serially numbered and records were kept with each casting made in each mold.

3. Techniques of Slip-Casting and Firing

All casting was carried out under pressure in order to reduce the time necessary to slip-cast the thick wall required (about 0.63-inch). Each plaster mold was provided with a steel cover plate having the necessary fittings for pressure casting. A typical setup for pressure slip-casting is shown schematically in Figure 6. Pressure was applied to the slip reservior at 10 psi for 10 minutes to allow the mold to fill completely and to allow the displaced air to escape through the plaster mold. Air pressure was then increased to 20 psi for the remainder of the casting period. All casting was carried out with the mold in the tip-up position.

In spite of the precautions taken in mold fabrication it was necessary to establish a casting time to produce the required 0.63-inch radome wall thickness for each mold. No mold release was used and only 3 castings were made in each mold before it was discarded.

The initial casting in each mold was based on the proper casting time found for the previous mold. A casting was made in the new mold and the dry wall thickness measured. If it was not within tolerance it was corrected using the formula:

$$\theta_2 = \theta_1 \frac{W_2^2}{W_1^2}$$

where: θ_1 = Initial casting time

θ_2 = New casting time

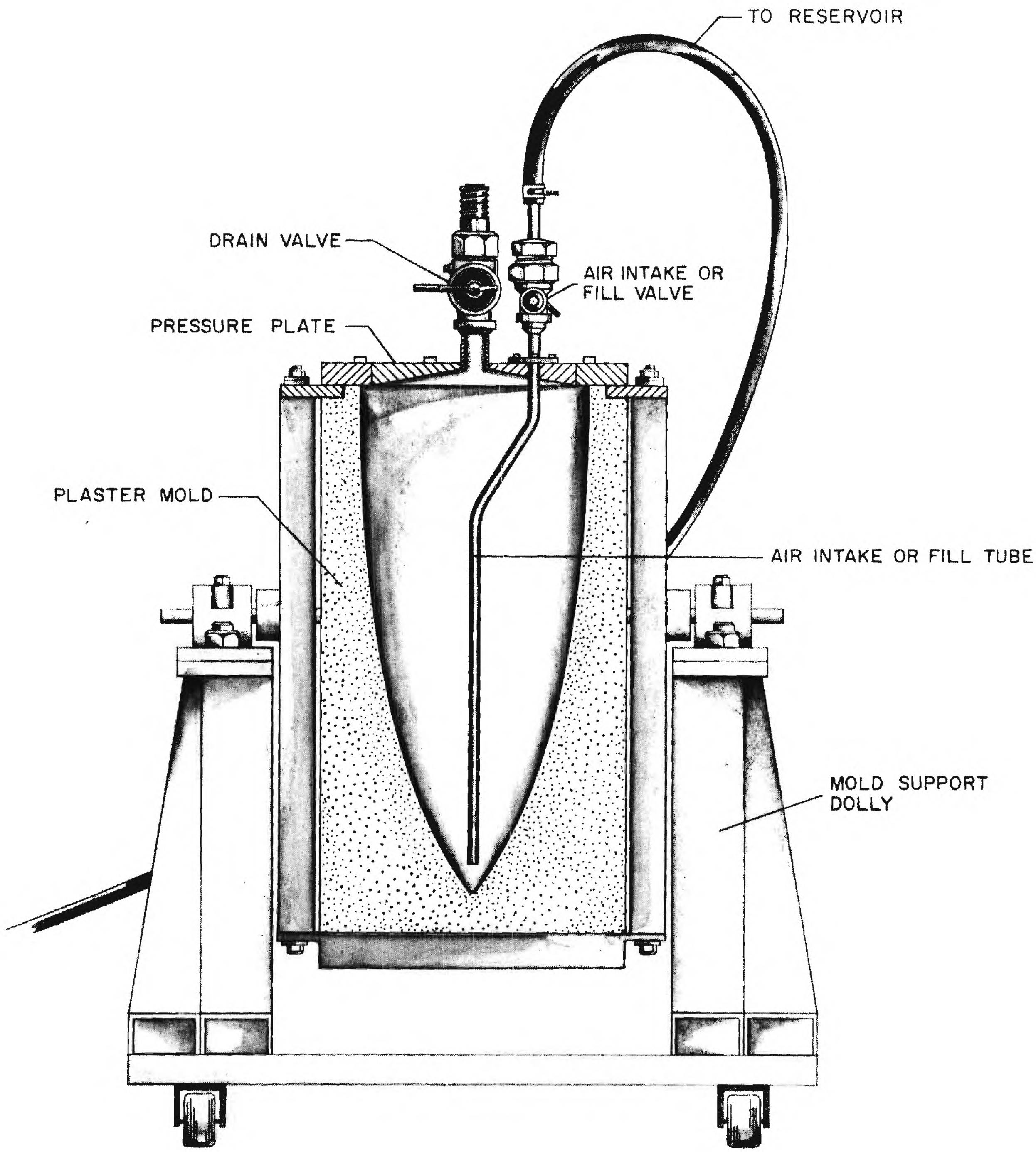

Figure 6. Typical Pressure Casting Setup for Slip-Casting Fused Silica Radome.

W_1 = Initial radome wall thickness

W_2 = Desired radome wall thickness

and a new casting made.

Each radome was allowed to dry 2 to 3 hours in the mold before handling. All radomes were handled with clear plastic gloves and were not touched with the hands until after heat treatment. This step is necessary to prevent localized devitrification of the radome surface from impurities, particularly sodium chloride from perspiration from the hands.

After removal from the mold each radome was dried for several days at room temperature and then heat treated in an electrical resistance heated furnace. Three radomes were heat treated at one time on a rotating pedestal within the furnace. The three radomes were placed on blankets of aluminum-silicate fibers and arranged on the pedestal in the furnace as shown in Figure 7. The heat treating schedule was as follows: 400° F for 4 hours, 1800° F for 16 hours, 1900° F for 4 hours, 2300° F for 2 hours 25 minutes. The furnace then was turned off and allowed to cool to 400° F before opening.

The qualified heat treated radomes had the configuration and tolerances shown in Figure 8. The wall thickness was measured utilizing the apparatus shown in Figure 9, and the radomes were then epoxy bonded to an aluminum base plate and set up in a lathe. Roundness measurements were made and the radome skirt cut off at the point shown in Figure 8. The skirt was used to obtain modulus of rupture (MR) and volume per cent cristobalite present in each radome. Cristobalite data and MR were obtained from each quadrant of the skirt to assure that the heat treating arrangement shown in Figure 7 had given

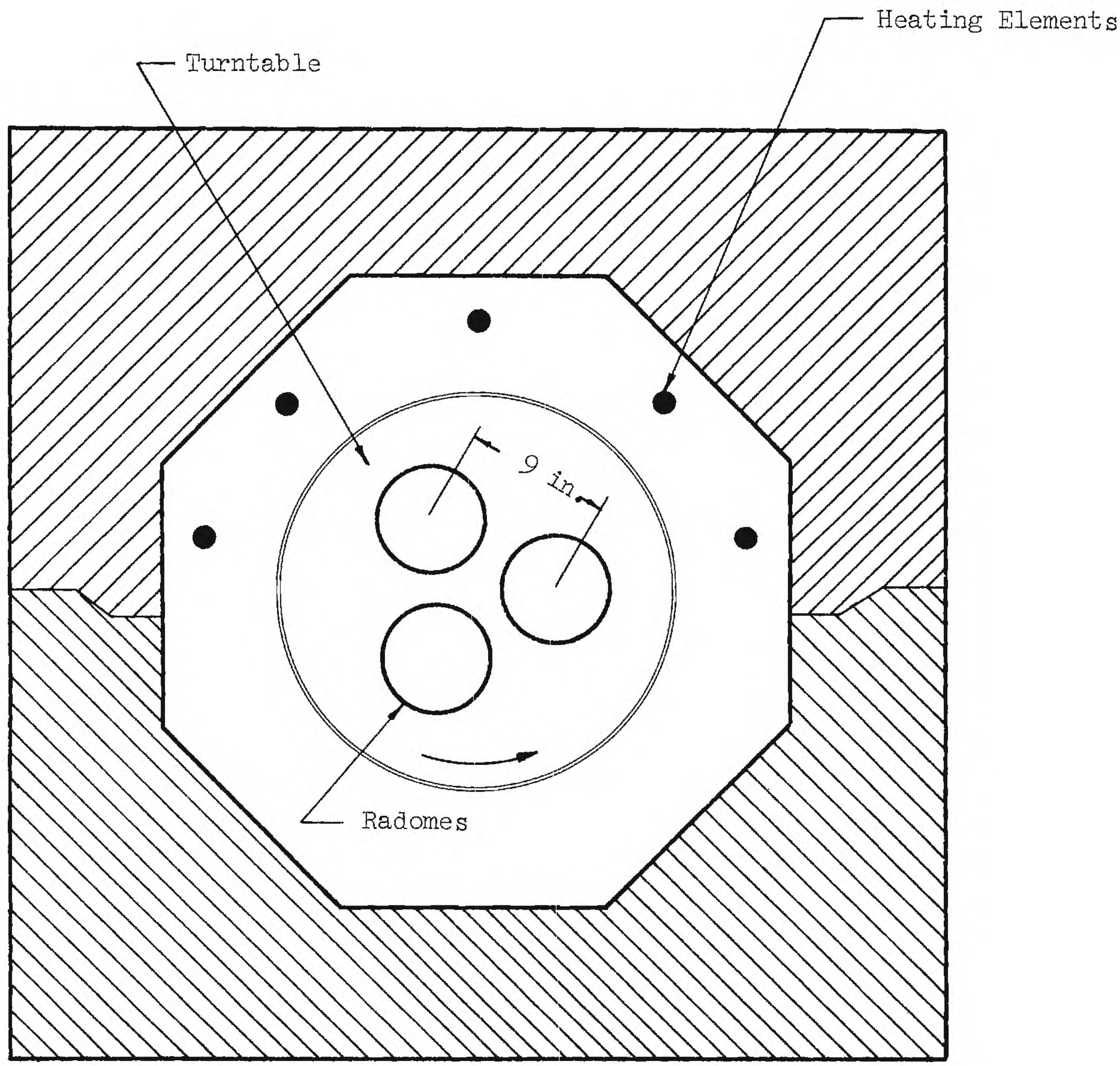

Figure 7. Schematic of Arrangement Used in Heat Treating Radomes in Furnace.

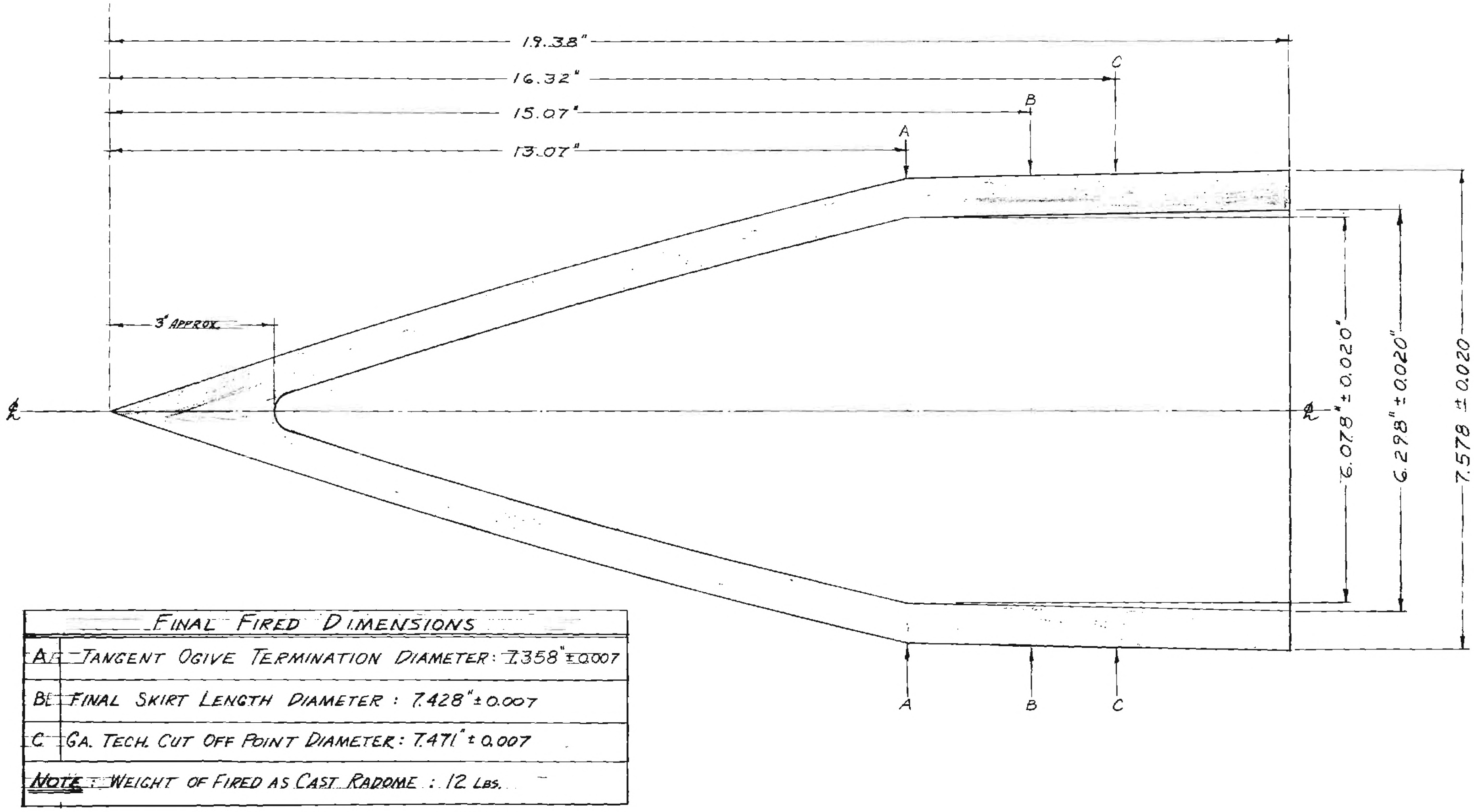

Figure 8. Configuration and Tolerances Used to Qualify Heat Treated Radomes.

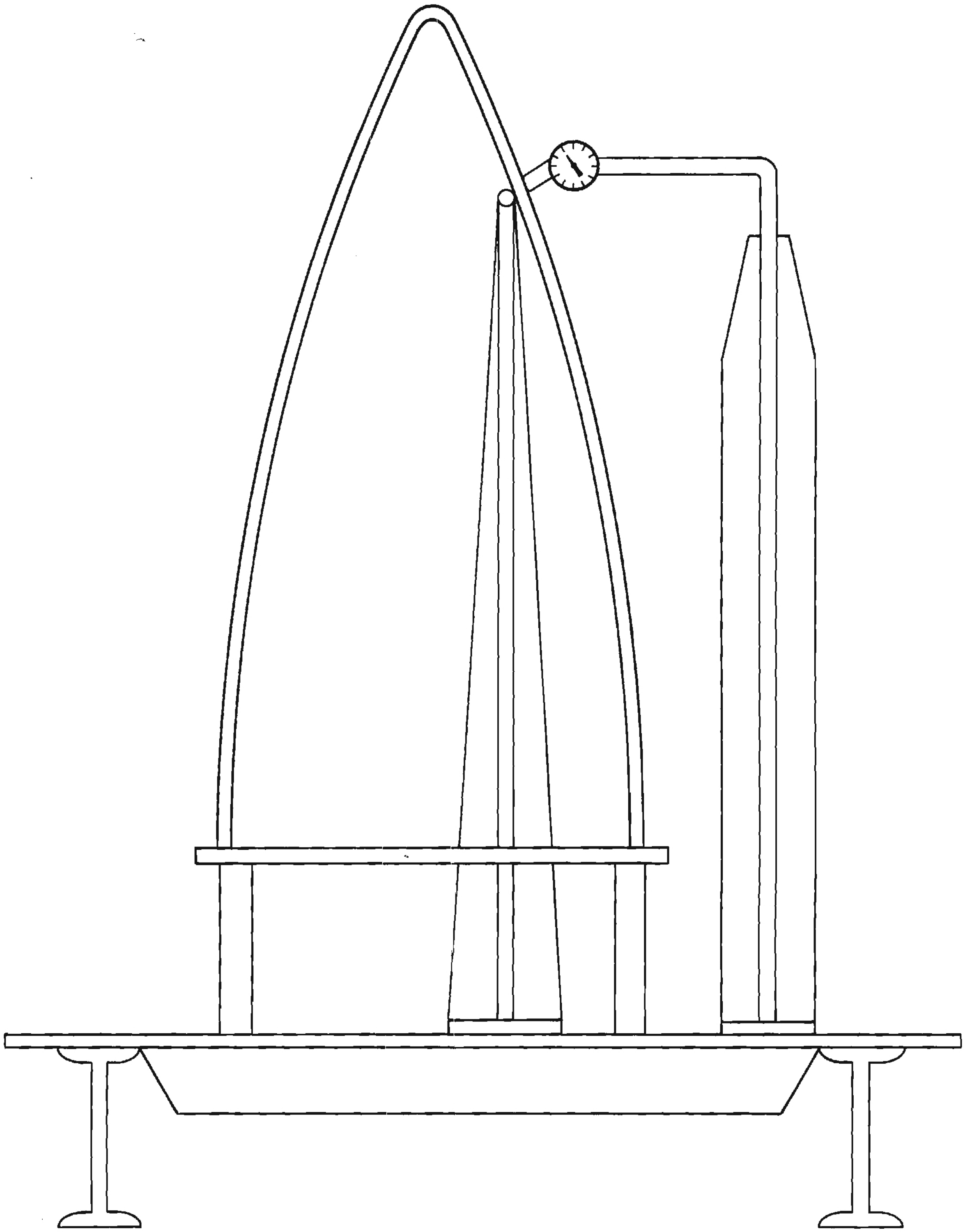

Figure 9. Drawing Illustrating Apparatus Used to Measure Wall Thickness of Radome Shapes up to Four Feet High.

a uniform heat treatment to all points of the radome. In addition, out of tolerance radomes were heat treated and the entire radome cut into MR specimens to assure that the radomes were receiving uniform heat treatment over their vertical length. Modulus of rupture specimens were broken transversely in center point loading on a 3-inch span and at a loading rate of 600 lb/minute. The broken MR specimens were ground to pass a 325 mesh screen (44 μ) and used for x-ray diffraction determination of cristobalite content. Table II shows the average MR and cristobalite content with 95 per cent confidence interval of the radomes used in the rain erosion test program.

TABLE II

HISTORY OF RADOMES SHIPPED TO GD/P FOR SELECTION OF FINAL TEST RADOMES AND INSTALLATION OF ATTACHMENT SYSTEM

Radome Serial No.	Mold No.	Casting Time	Skirt Wall Thickness				Modulus of Rupture	Bulk Cristobalite
			North	East	South	West		
		(min)	(in)	(in)	(in)	(in)	(psi)	(v/o)
1007	314	170	0.633	0.649	0.643	0.651	4764 ± 264	7.0 ± 1.0
1612	412	181	0.647	0.647	0.652	0.651	4642 ± 405	7.7 ± 0.1
2723	614	180	0.633	0.634	0.634	0.637	4501 ± 299	9.1 ± 0.8
1411	411	155	0.639	0.639	0.648	0.645	4850 ± 398	8.3 ± 0.4
3327	712	170	0.609	0.603	0.617	0.622	5314 ± 500	9.7 ± 1.0
3430	811	170	0.617	0.640	0.647	0.649	---	8.7 ± 2.0
1745	1001	170	0.668	0.664	0.681	0.673	---	5.3 ± 0.3

The satisfactory radomes were flame glazed using a plasma jet to fuse the surface. This provided a coating of nonporous fused silica that served to seal the surface. This thickness of the fused layer varied from about 0.030 to 0.040-inch near the tip to less than 0.005-inch near the base of the radome.

The flame glazed radomes and the one unglazed radome were sent to General Dynamics/Pomona for installation of the attachment ring, and metal tip. The radome assemblies were subjected to vibrational proof tests and boresight tests and then shipped to Holloman Air Force Base for rain erosion sled tests. The domes that survived the rain test were returned to GD/P for subsequent boresight tests (Part II).

VI. RAIN EROSION SLED TEST RESULTS

Table III summarizes the sled tests carried out at Holloman Air Force Base during the period 27 June through 20 December 1966.

TABLE III

SUMMARY OF RAIN EROSION TEST RESULTS

Run No.	Holloman No.	Radome Serial No.	Rain Field (ft)	Rain Entrance Velocity (ft/sec)	Rain Exit Velocity (ft/sec)	Maximum Velocity (ft/sec)	Remarks
1	7RA2A	1007	None	----	----	5530	Radome hit bird during coast out at about 1500 ft/sec.
2	7RB1	2723	400	5250	5350	5443	Erosion effects consisted of surface dimples covering about 50% of the surface.
3	7RC1	1411	800	5400	5550	5599	The first 3-1/2 inches of the radome were lost when the sled hit the water brake. Surface erosion was twice Run No. 2.
4	7RD1	3430	2000	5050	4600	5100	Moderate surface erosion resulted from rain impingement.
5	7RE1	1612	4000	5200	---	5420	The radome broke up after about 2000 ft in the rain.
6	7RE2A	3327	4000	4870	---	5345	The radome broke up after about 3000 ft in the rain.

(Continued)

TABLE III (Continued)

SUMMARY OF RAIN EROSION TEST RESULTS

Run No.	Holloman No.	Radome Serial No.	Rain Field (ft)	Rain Entrance Velocity (ft/sec)	Rain Exit Velocity (ft/sec)	Maximum Velocity (ft/sec)	Remarks
7	7RF2	1745	2000	4570	5190	5430	Moderate surface erosion (< 7RD1) resulted on front 4-in. of radome. Radome hit bird during coast out at about 3000 ft/sec.

A. Run No. 1 (7RA2A)

Figure 10 shows radome No. 1007 after impact with a bird. From image motion photographs it could be seen that the radome was undamaged until the bird was hit. From velocity profile data obtained from this run it was estimated that the sled had coasted to a speed of about 1500 ft/sec when it hit the bird.

B. Run No. 2 (7RB1)

Figures 11, 12, and 13 show radome No. 2723 after exposure to 400 feet of rain. From these photographs it can be seen that practically every drop caused some surface damage. No other damage was observed.

C. Run No. 3 (7RC1)

Figures 14 and 15 show radome No. 1411 after exposure to 800 feet of rain. The broken tip suggested that the radome probably broke during or upon leaving the rain field. At this time sled vibration would be at a maximum.

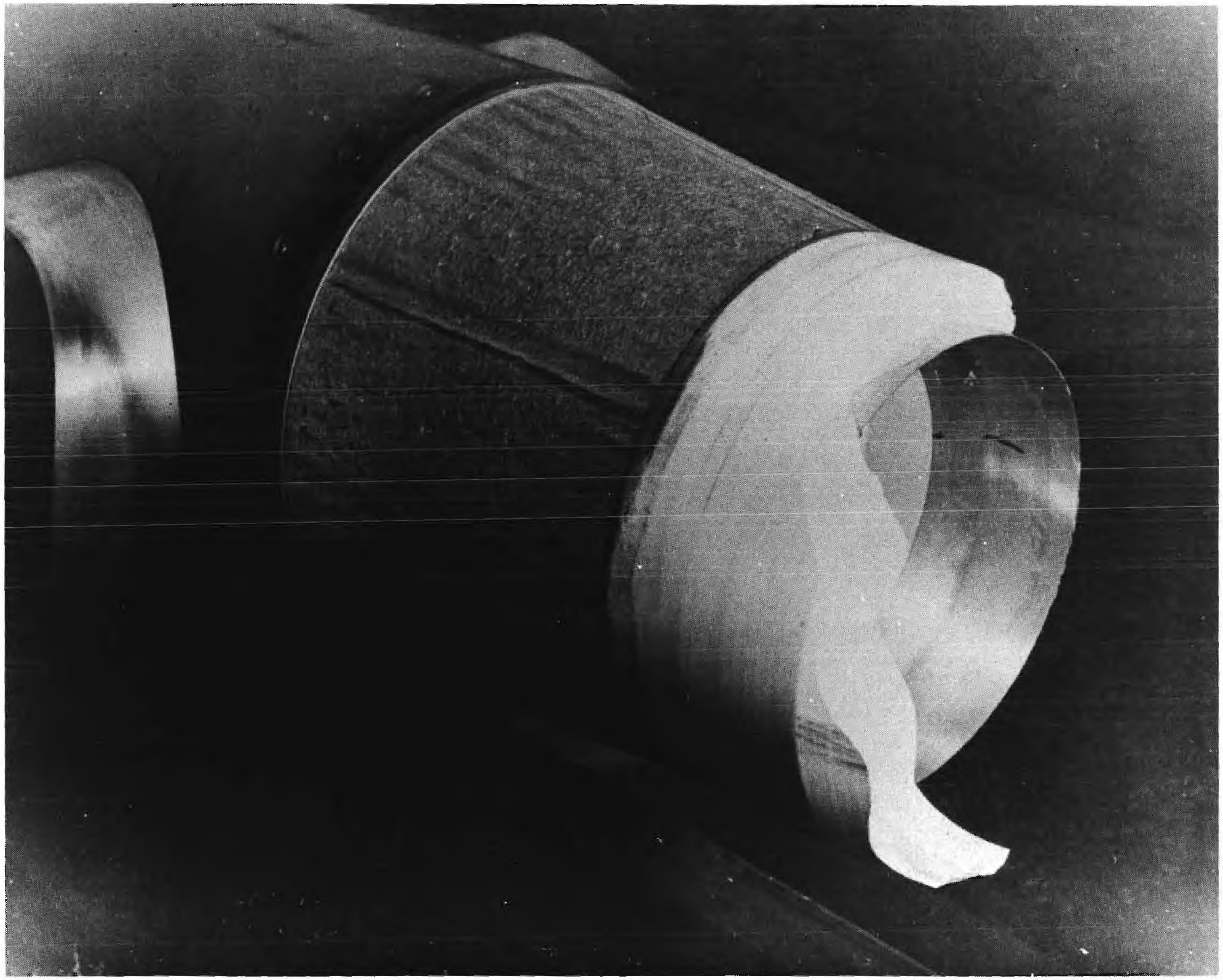

Figure 10. Radome from Run No. 1 after Hitting Bird (7RA2A).

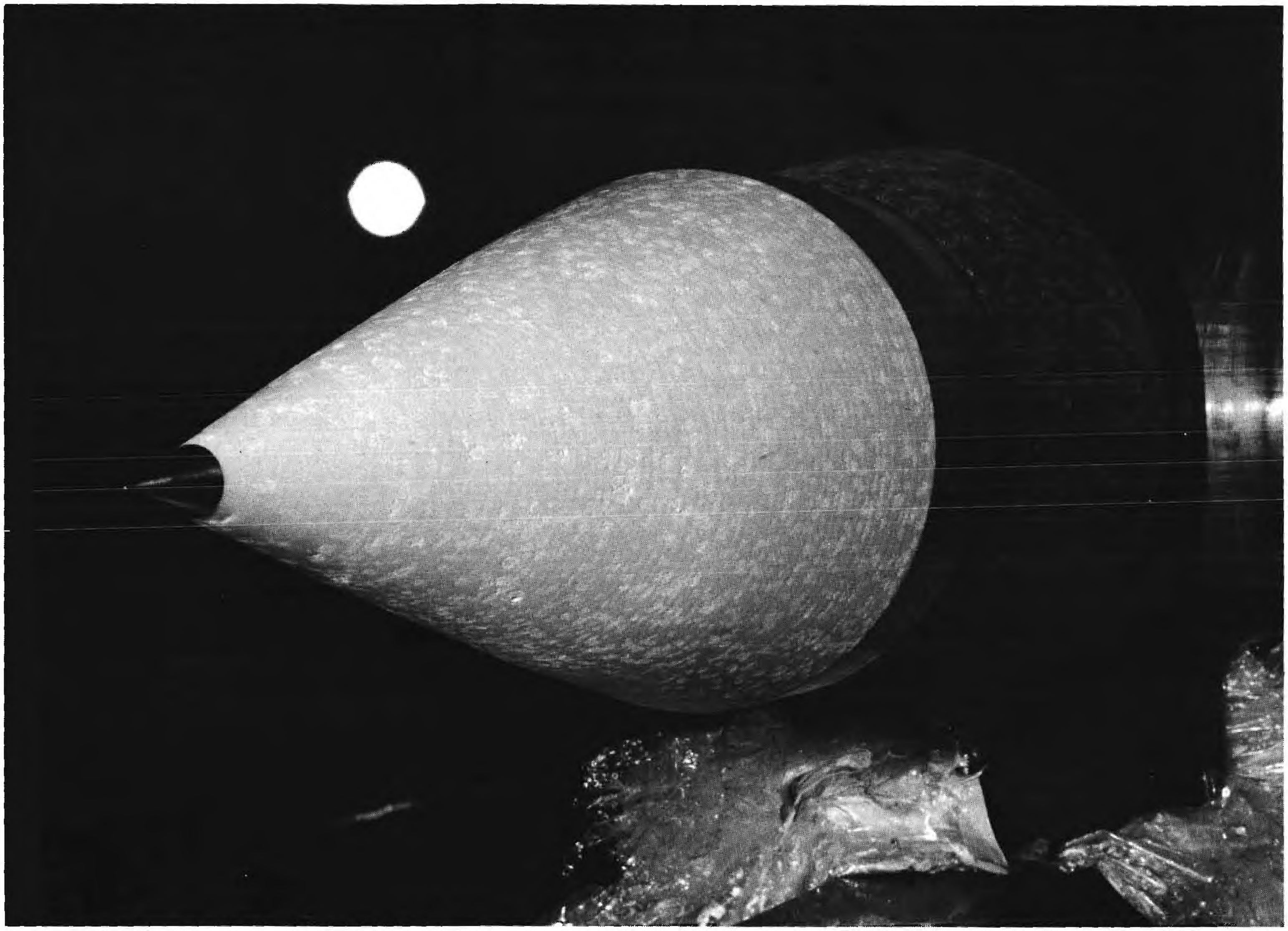

Figure 11. Radome on Sled after 400 Feet of Rain in Run No. 2 (7RB1).

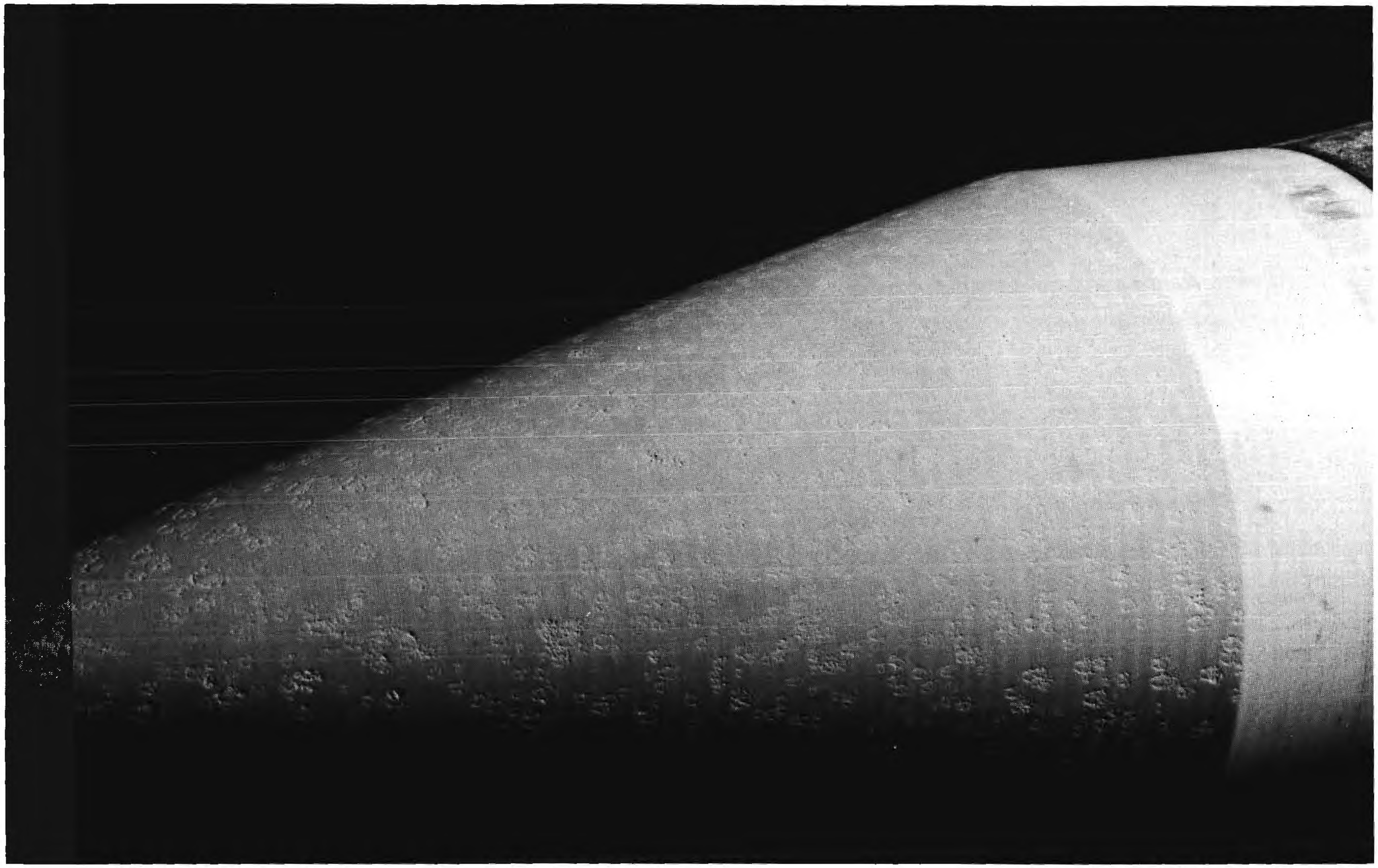

Figure 12. Close-up of Radome from Run No. 2 (7RB1).

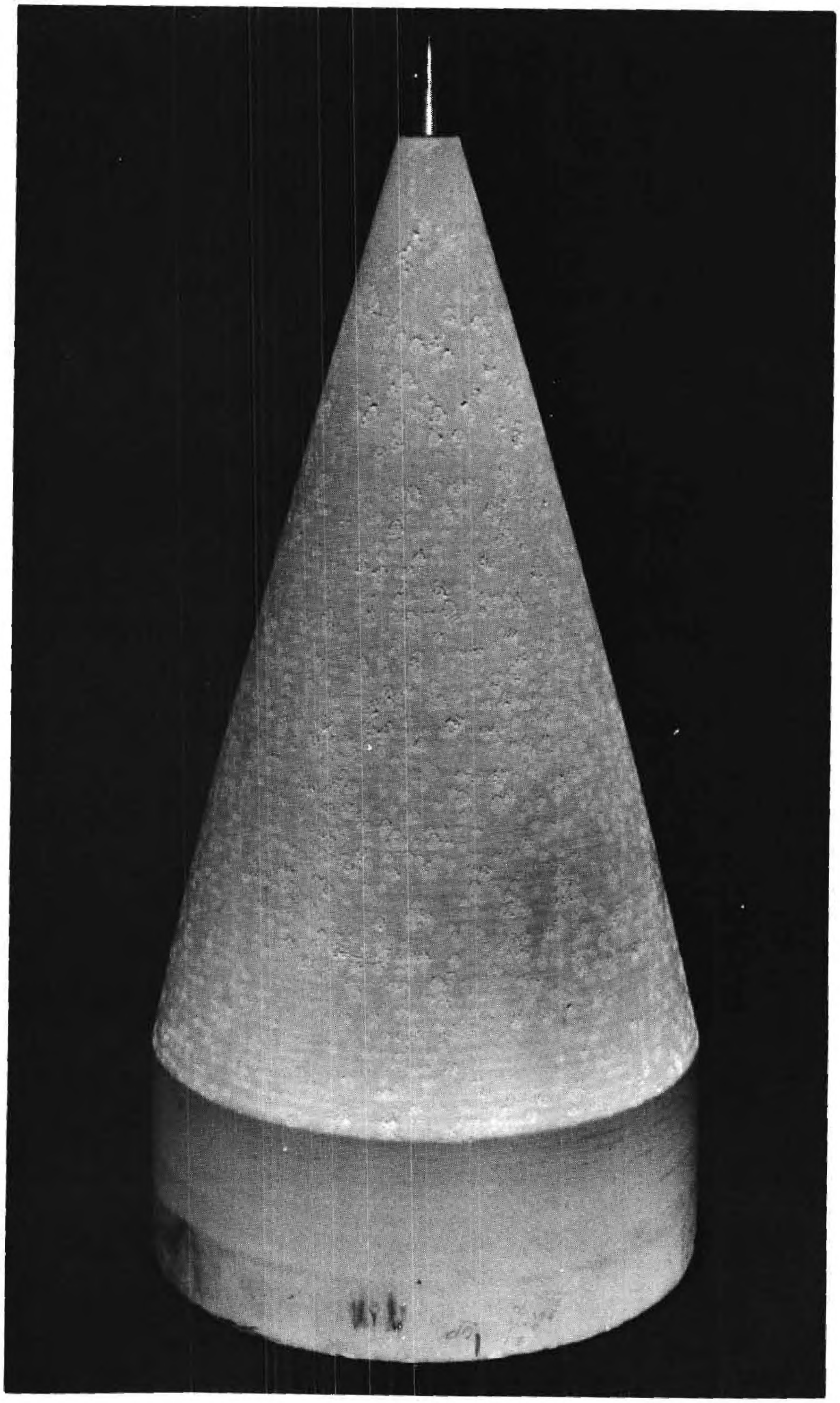

Figure 13. Side View of Radome from Run No. 2 (7RB1).

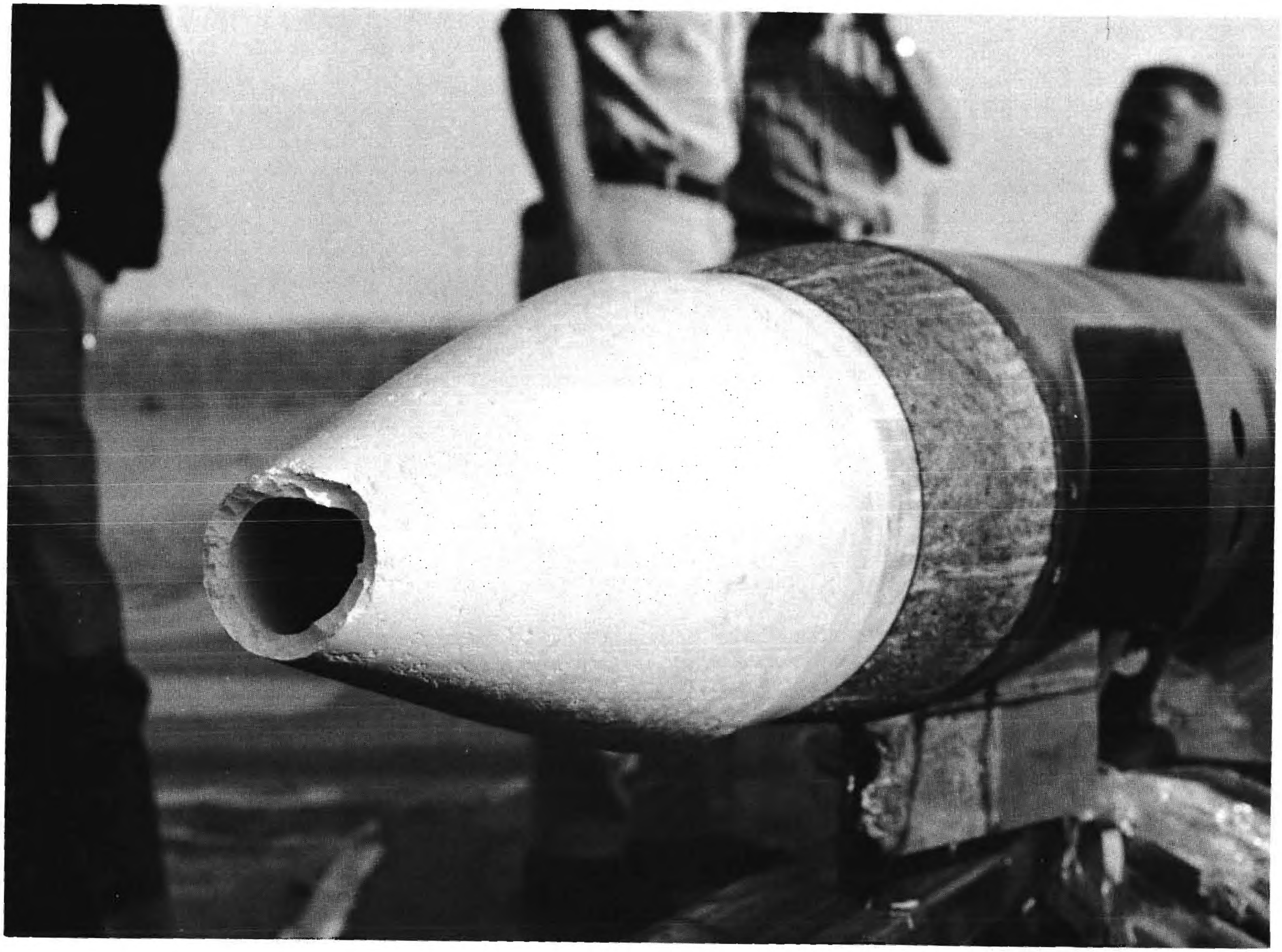

Figure 14. Radome on Sled after 800 Feet of Rain in Run No. 3 (7RC1).

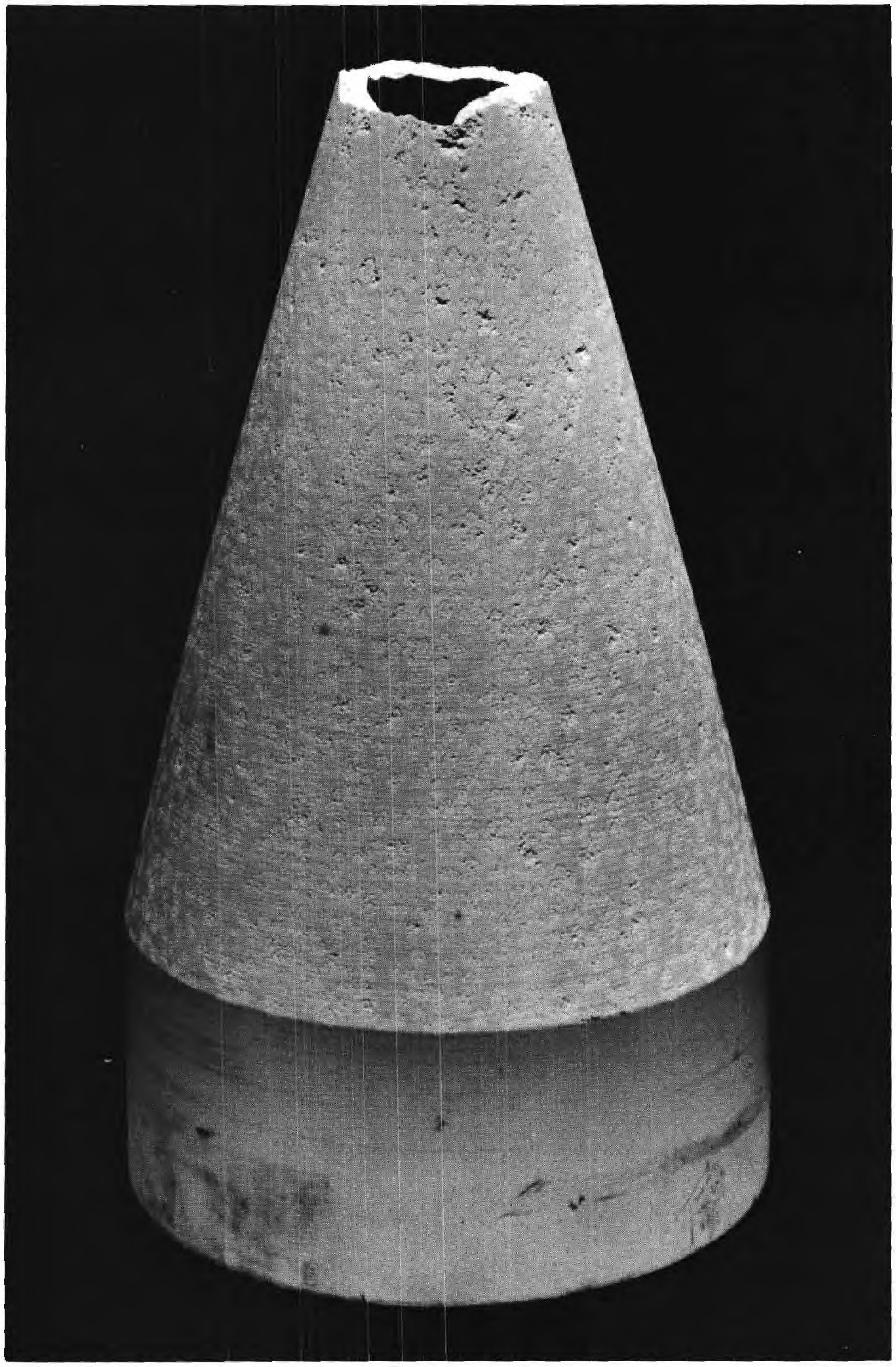

Figure 15. Side View of Radome from Run No. 3 (7RC1).

However, from the image motion photograph shown in Figure 16 it can be seen that the radome was intact when it emerged from the rain field. It can also be seen that the drag brakes (cylindrical piece protruding from the side of the sled just aft of the transition piece which connects the radome to the sled) are almost completely extended. This information suggested that the radome tip probably survived the high velocity portion of the flight and that the portion of the radome may have come off as a result of the high deceleration associated with the sled hitting the water brake. Subsequent search of the water brake area uncovered the broken tip about 800 feet from the point where the sled first encountered the water brake.

D. Run No. 4 (7RD1)

Figures 17 and 18 show radome No. 3430 after exposure to 2000 feet of rain. A cross wind from the East of about 3 knots provided an estimated rain rate of 3.6 inches per hour. Although there was evidence of some erosion over the entire surface, it did not appear more severe than would be predicted from Runs No. 2 and 3. Also, the majority of the damage appeared on the forward 5 inches of the cone. Aft of this point the severity of the damage decreased rapidly.

E. Run No. 5 (7RE1)

Figures 19, 20, and 21 are image motion camera photographs of radome No. 1612. Figure 19 is from IMC-6 and shows the radome just before it entered the rain field. Figure 20 is from IMC-2 and shows the radome after about 1500 feet of rain. Figure 21 is from IMC-3 and shows the sled just after the radome had broken up. Figure 22 shows the attachment ring after the run. Rain damage on the attachment itself is evident on the left side of the ring where it had

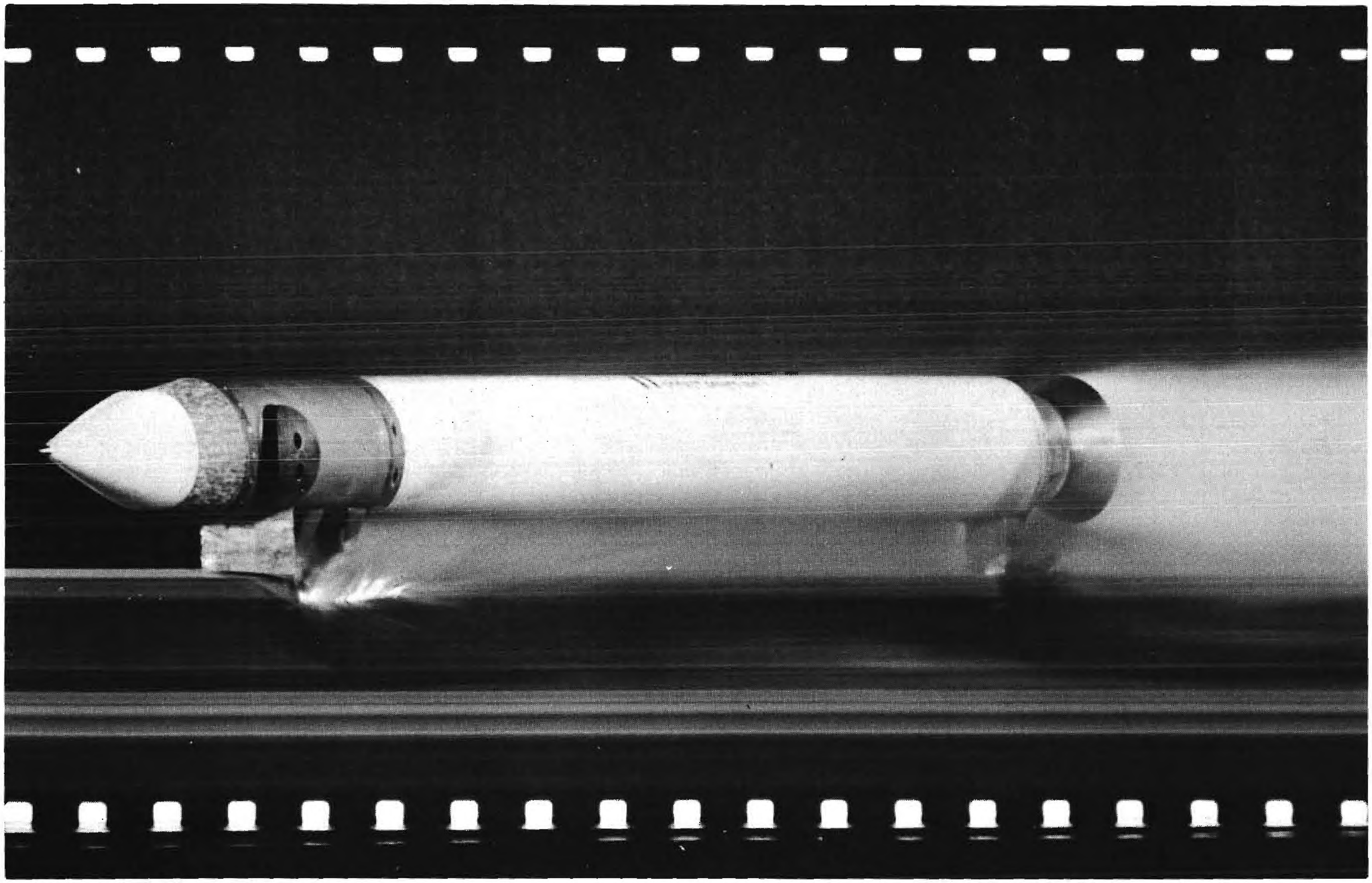

Figure 16. Image Motion Camera Photograph of Sled after Leaving 800 Foot Rain Field in Run No. 3 (7RC1).

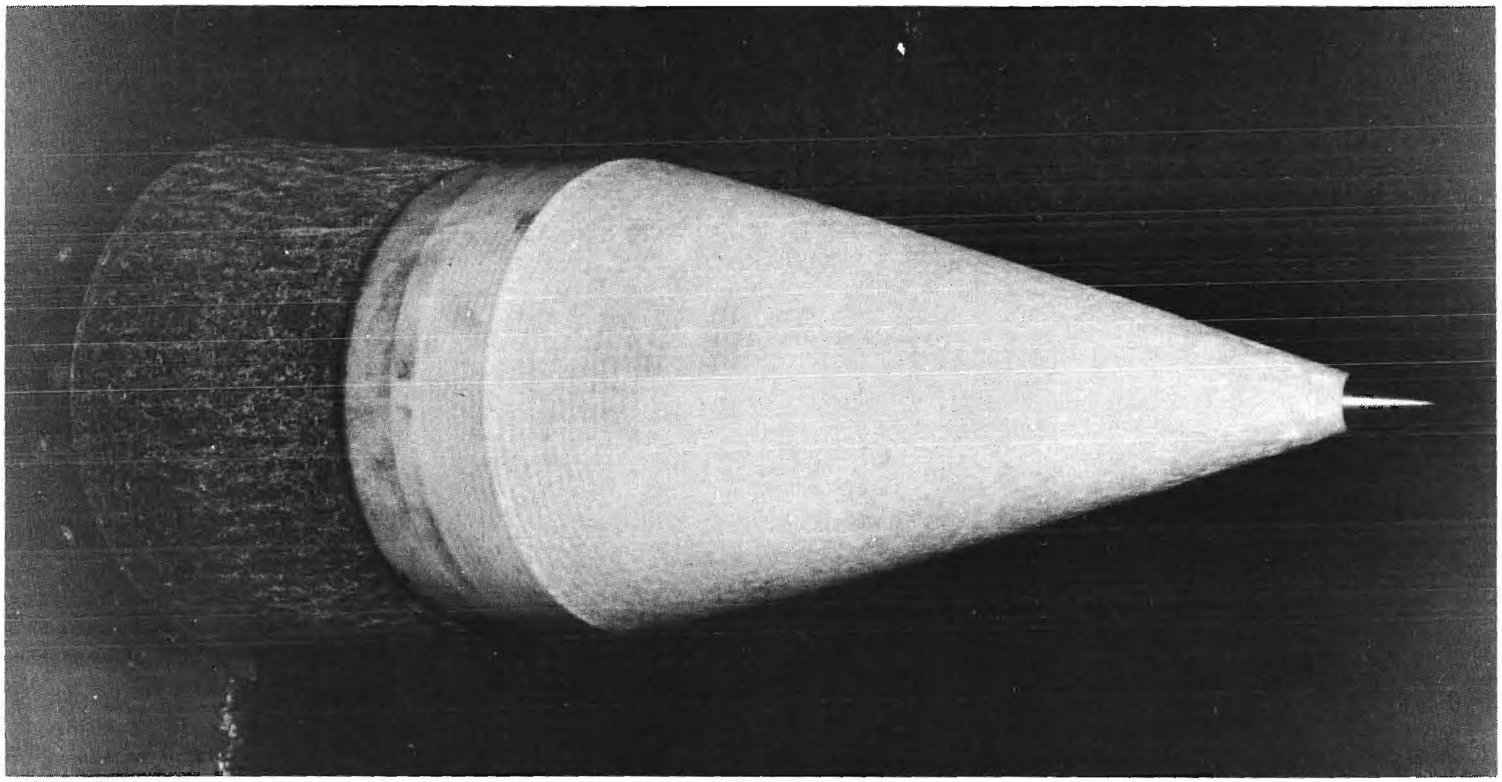

Figure 17. Radome on Sled after 2000 Feet of Rain in Run No. 4 (7RD1).

Figure 18. Side View of Radome from Run No. 4 (7RD1).

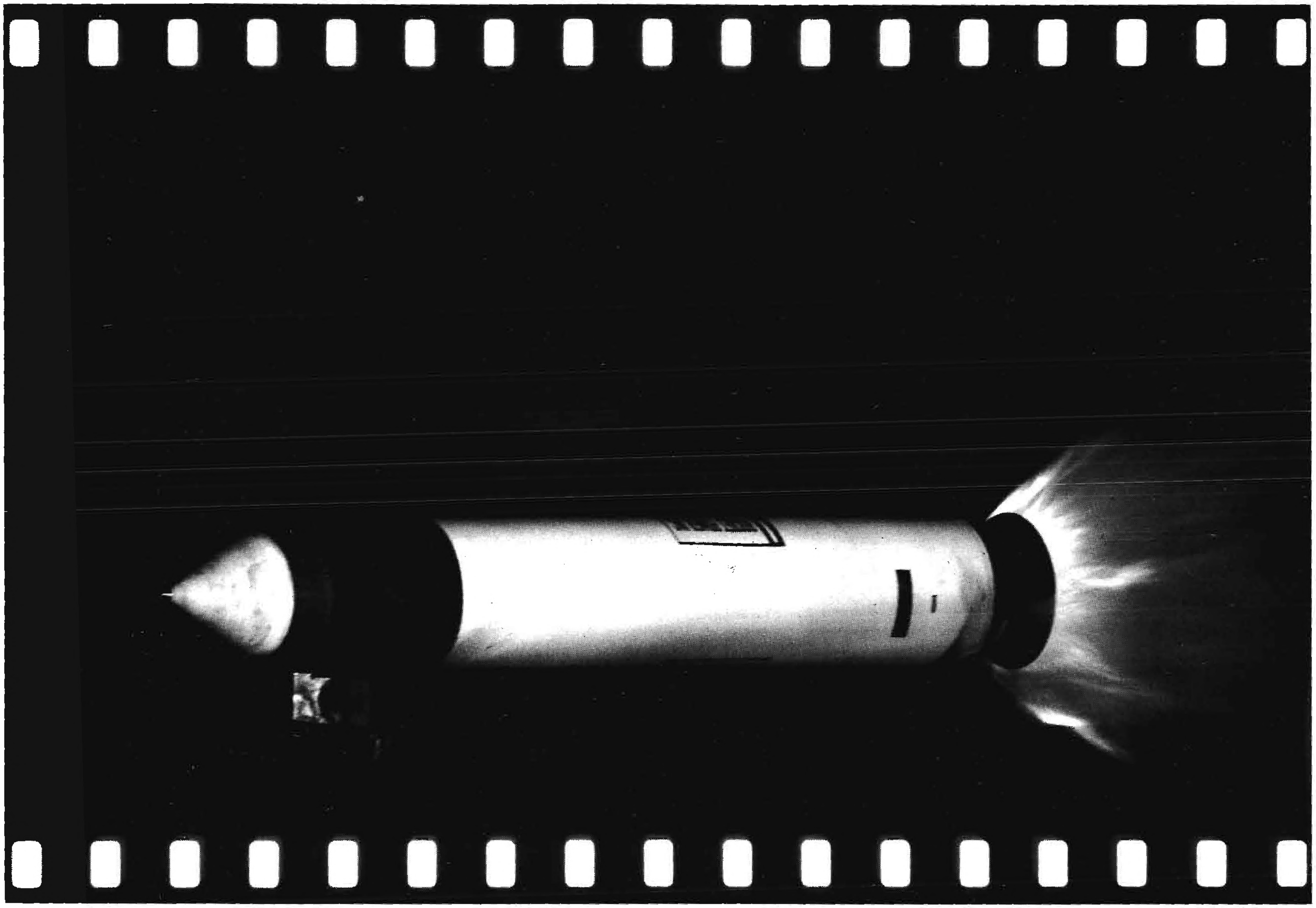

Figure 19. Image Motion Camera Photograph of Sled Entering 4000 Foot Rain Field in Run No. 5 (7RE1).

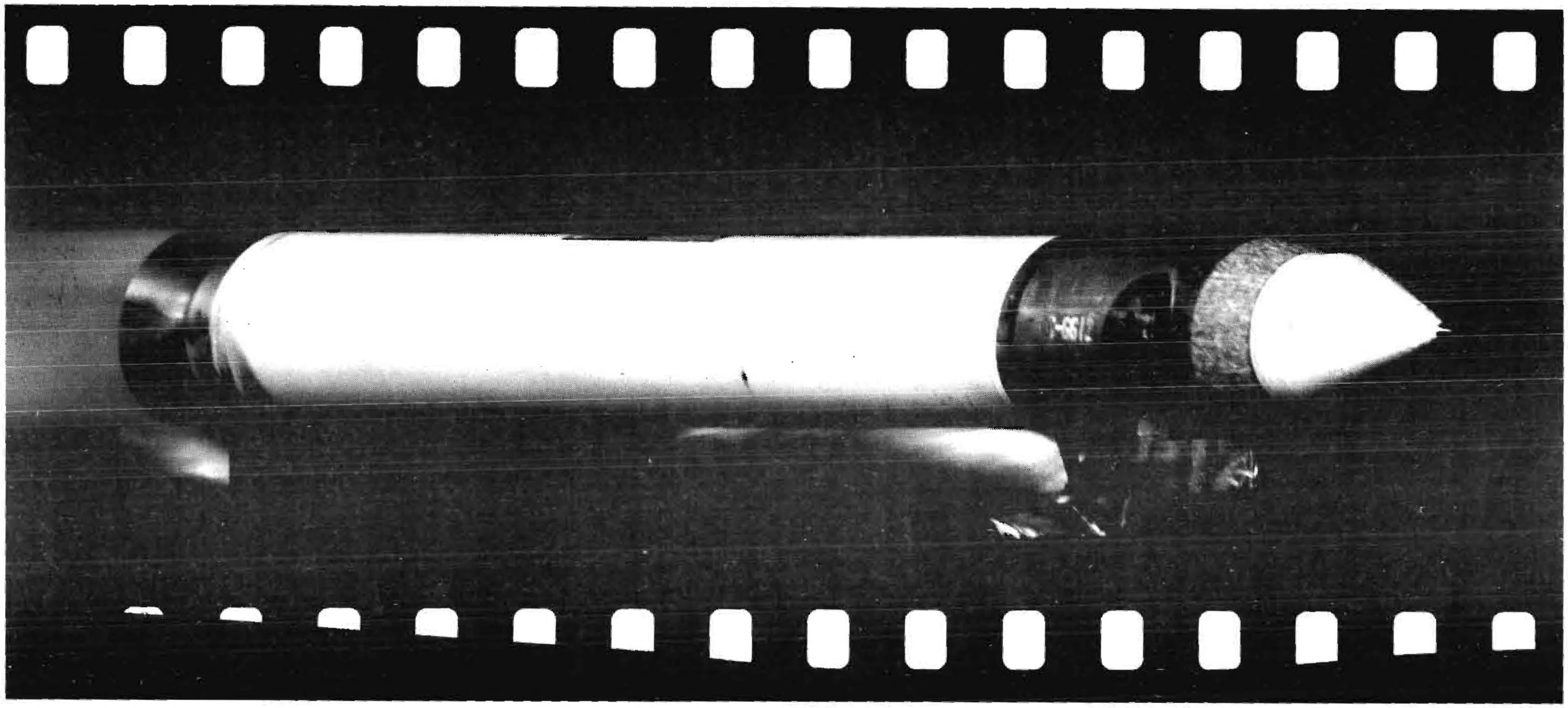

Figure 20. Image Motion Camera Photograph of Sled after about 1500 Feet in Rain Field in Run No. 5 (7RE1).

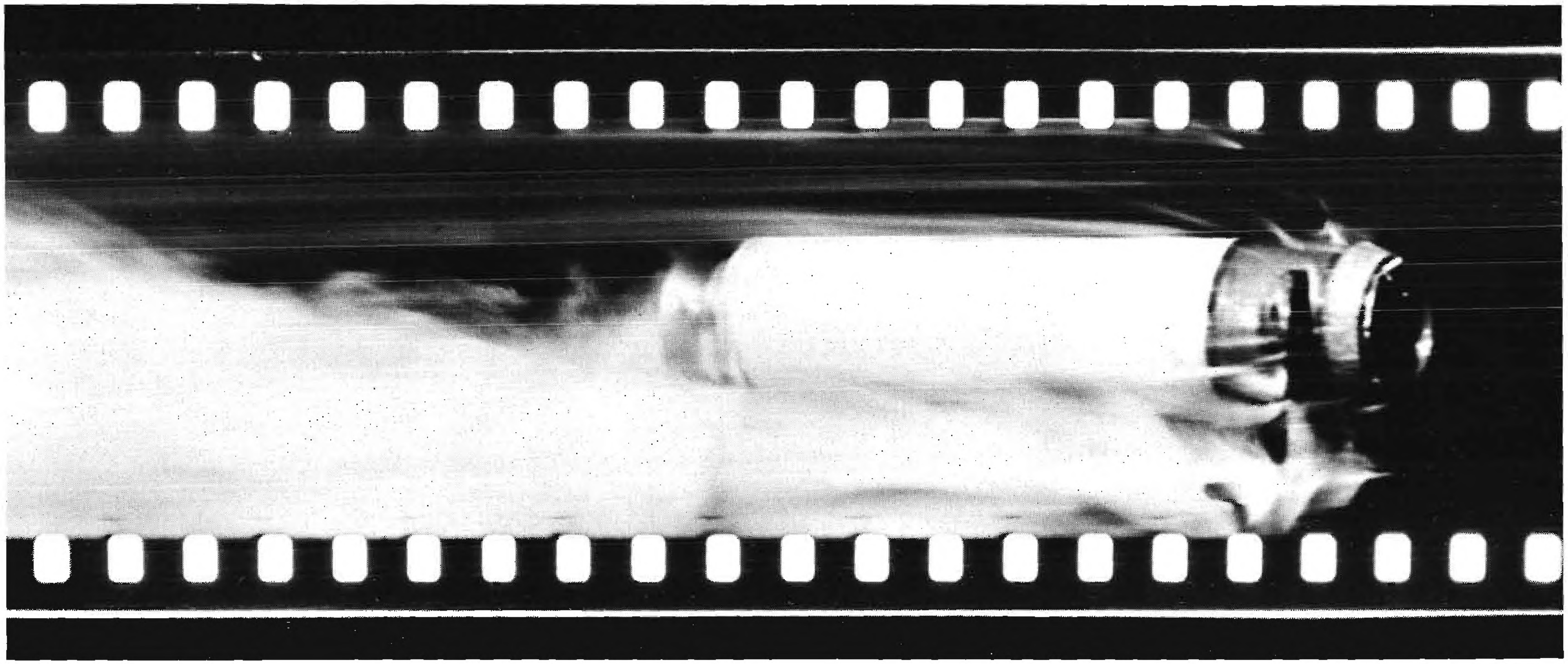

Figure 21. Image Motion Camera Photograph of Sled after about 2400 Feet in Rain Field.

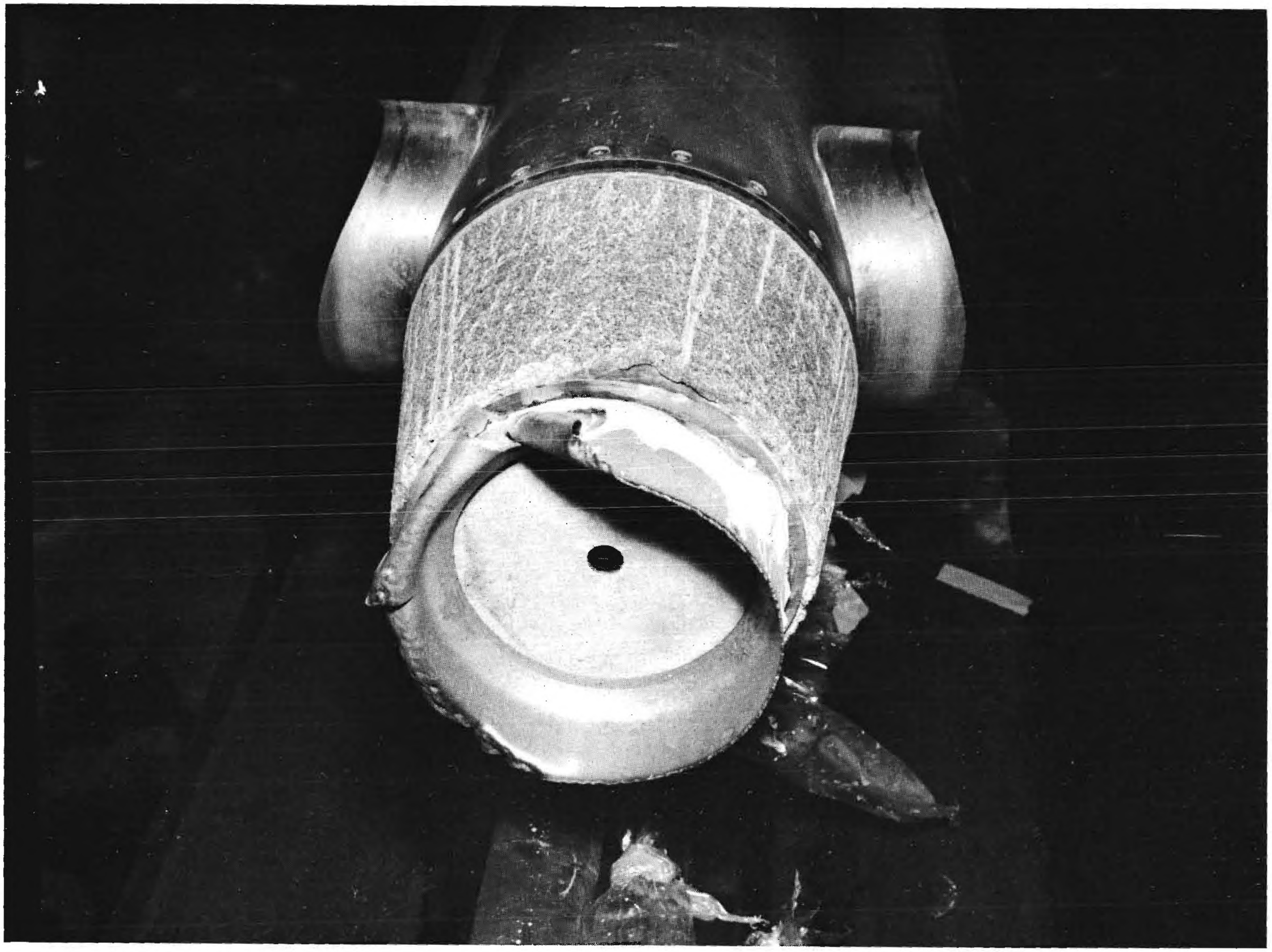

Figure 22. Attachment Ring on Sled after Run No. 5 (7RE1).

been peeled back due to aerodynamic forces. Figure 23 shows the location of the image motion cameras, the broken shower head and the rain field on the sled velocity vs distance curve for Run No. 5. The broken shower head confirmed the fact that the radome broke up after about 2000 feet in the rain. Figure 24 shows two portions of radome No. 1612 found near the broken shower head. The piece on the left is from the radome at a point about 6 inches from the tip of the radome. The piece on the right was located about 2 to 3 inches below the tip of the radome.

F. Run No. 6 (7RE2A)

Radome 3327 performed very much like 1612 from Run No. 5 except that it survived about 3000 feet of rain before breaking up. Figure 25 shows the location of image motion cameras, punctures in shower pipe and the rain field on the sled velocity vs distance curve for Run No. 6. Image motion camera 3 showed the radome on the sled, IMC-4 showed no radome on the sled.

G. Run No. 7 (7RF2)

Figure 26 is an image motion camera photograph showing radome No. 1745 after leaving the rain field and shows the radome still intact. Figure 27, the velocity profile for this run, indicates the location of the rain field and the area where pieces of the radome were found. Bird feathers found near track station 18,000 and the pieces of the radome found between track station 17,700 and 15,940 indicate that a bird was hit. Break wire data indicate the velocity of the sled at impact was about 3000 ft/sec. The tip section was found 100 feet west of track station 15,940. An adjoining section which mates perfectly with the tip section was found 95 feet west of station 16,800. Figure 28 shows the tip section, the largest piece found, compared with the

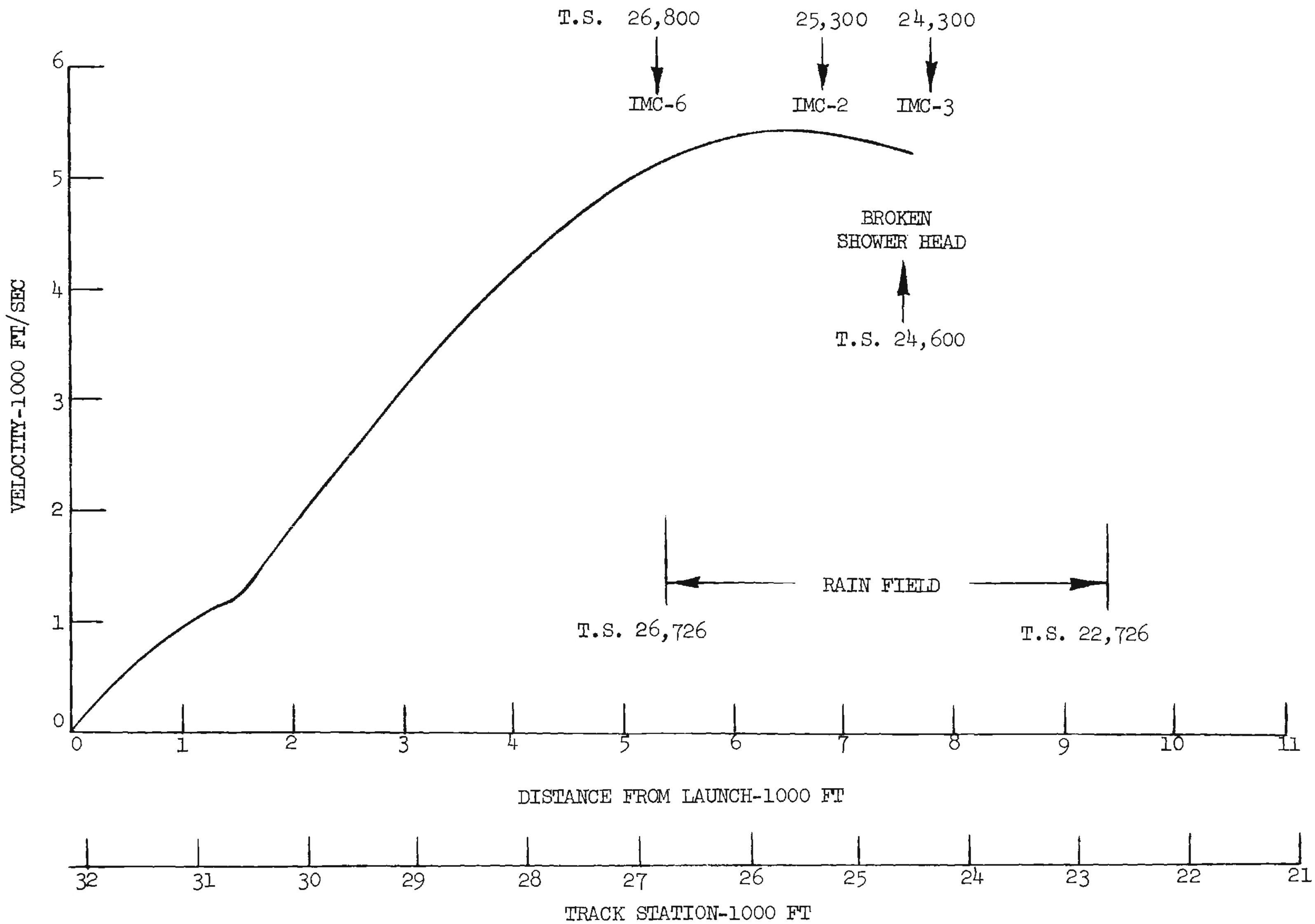

Figure 23. Sled Track Data for Run No. 5 (7RE1).

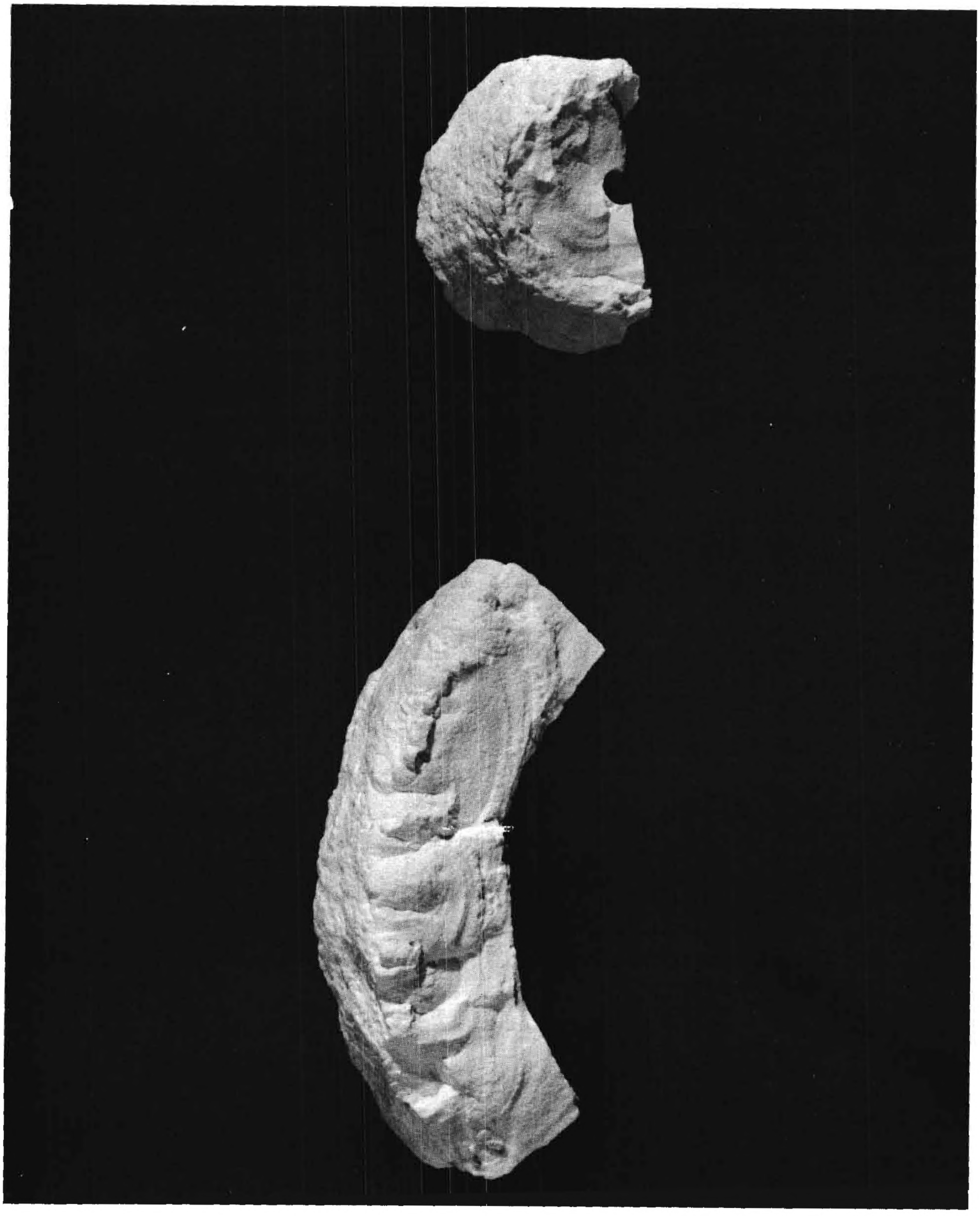

Figure 24. Broken Pieces of Radome from Run No. 5 (7RE1).

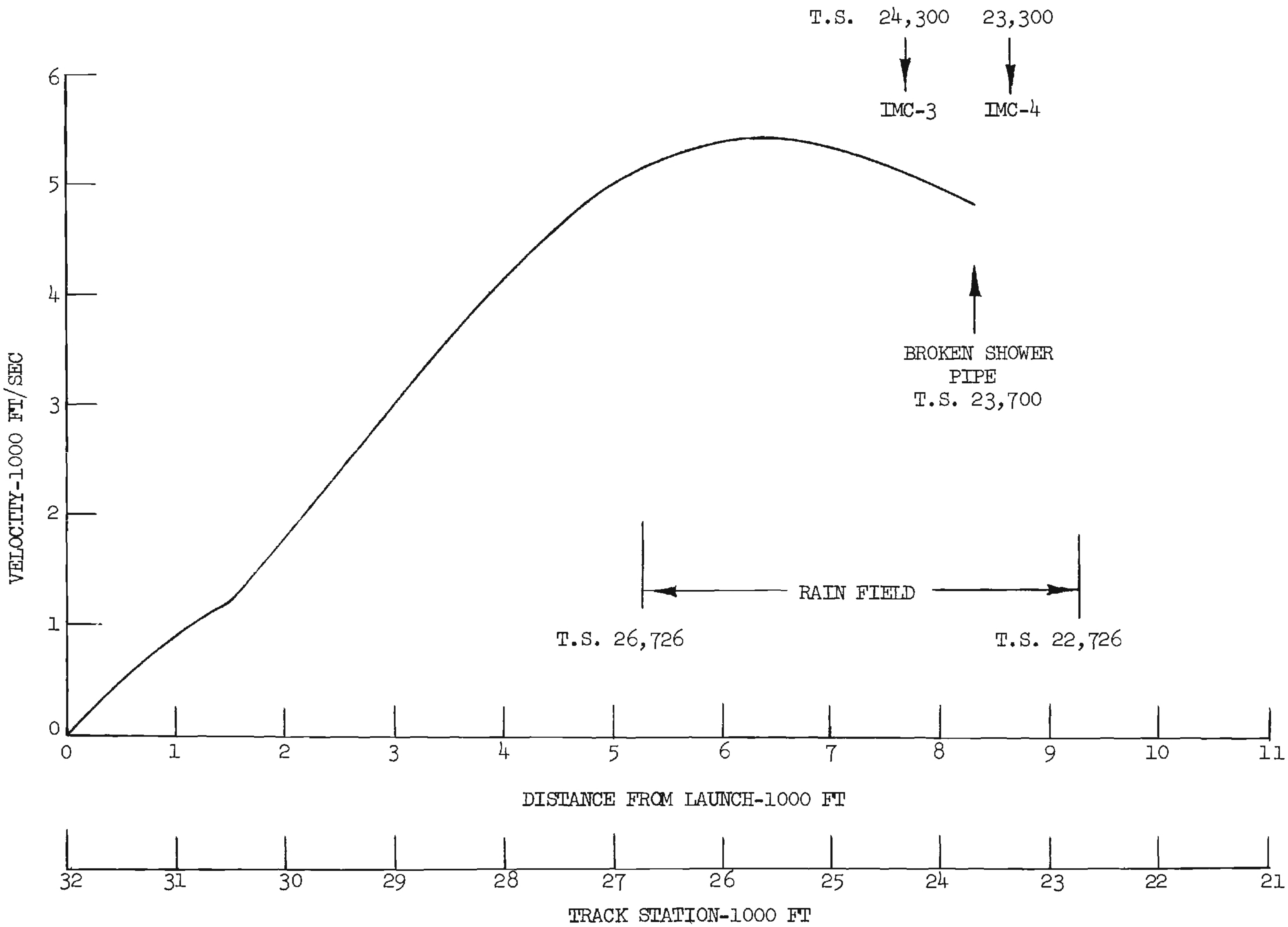

Figure 25. Sled Track Data for Run No. 6 (7RE2A).

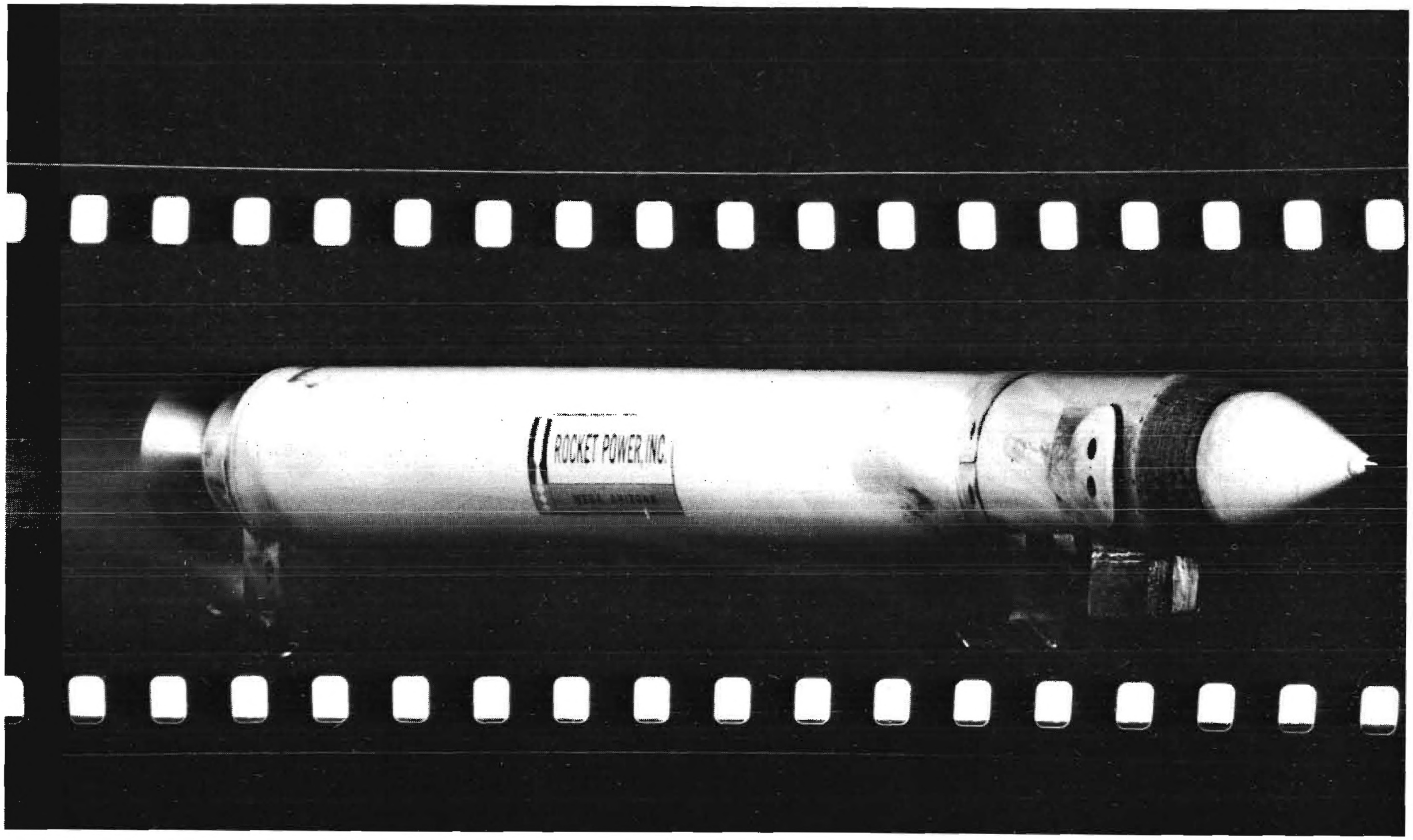

Figure 26. Image Motion Camera Photograph of Sled After Leaving 2000 Foot Rain Field in Run No. 7 (7RF2).

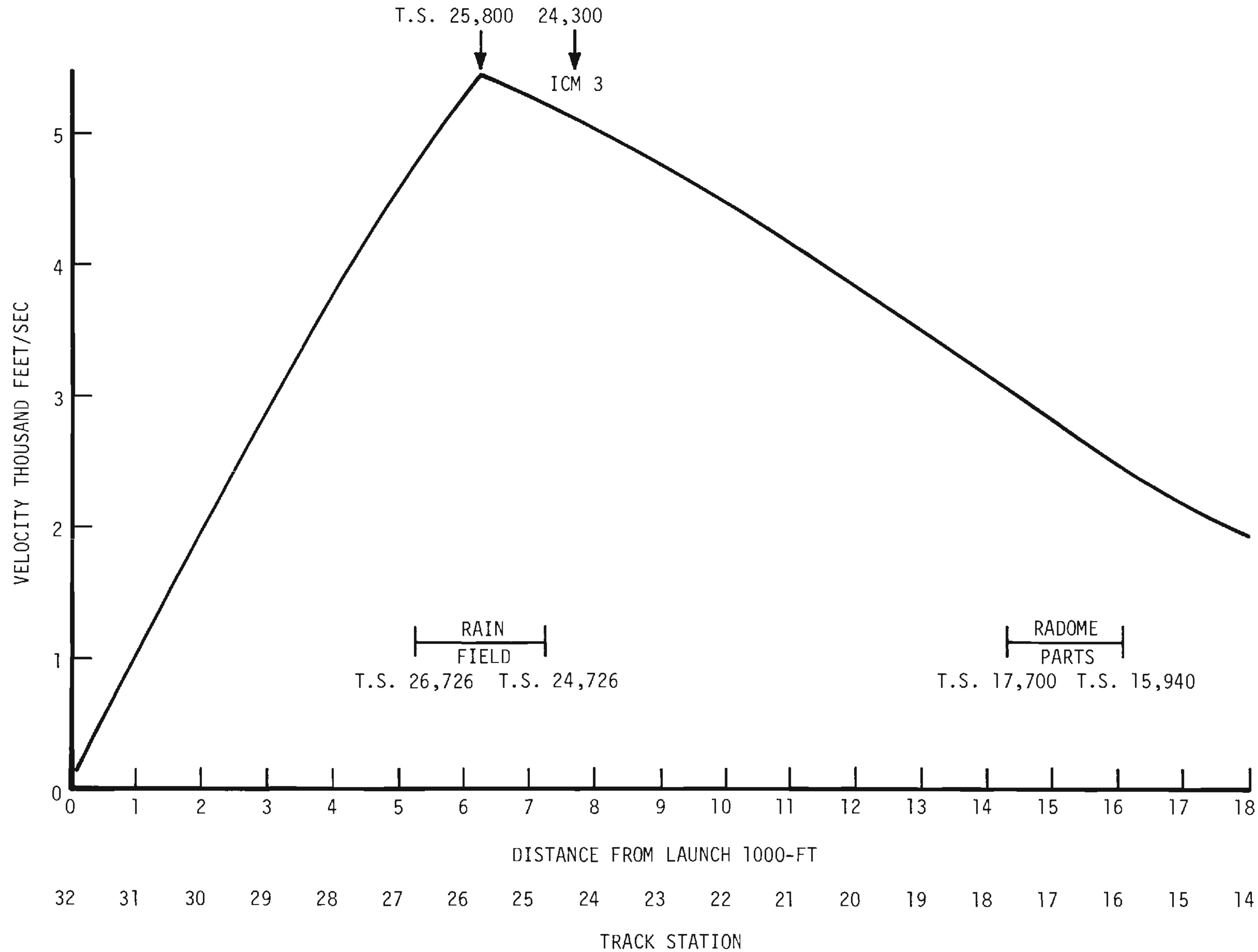

Figure 27. Sled Track Data for Run No. 7 (7RF2).

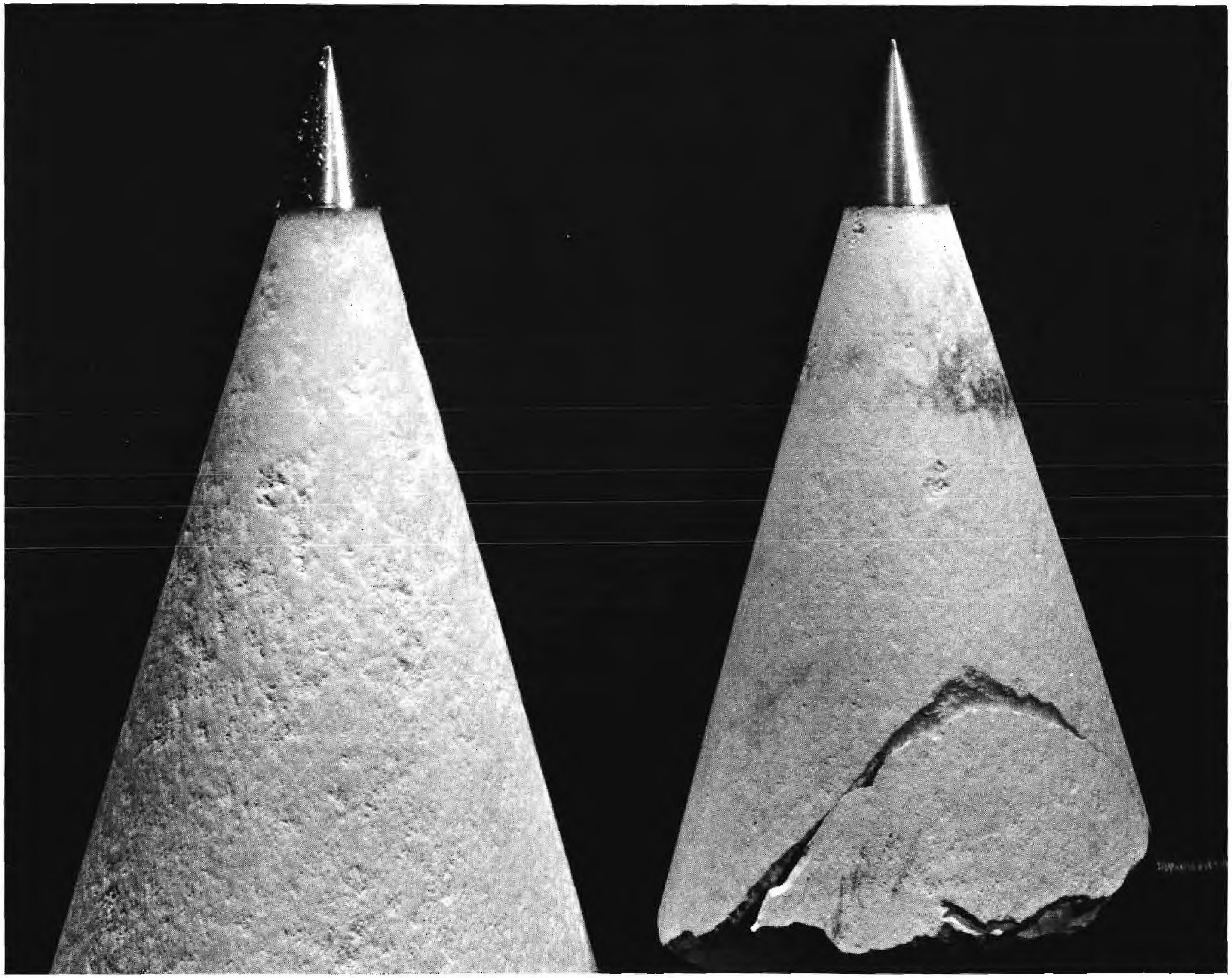

Figure 28. Side View of Radome From Run No. 4 (7RD1) and Radome Tip From Run No. 7 (7RF2).

glazed radome from run No. 4 (7RD1) which was also through 2000 feet of rain. Rain erosion on the intact tip section was mugh lighter than that on the same region of the radome from Run 7RD1.

VII. DISCUSSION OF RESULTS

A. Run No. 1 (7RA2A)

From Run No. 1 it was determined that the slip-cast fused silica radome could survive the sled environment. Although the lateral and vertical accelerations are not known, it would be expected that, at these high velocities, they would be much higher than would be expected in an actual missile flight. The normal, or axial acceleration is known to be of the order of 150 g's. As shown in Figure 4, this provided a velocity of 5600 feet per second, 4 seconds after launch. Also, it would be expected that the radome would be subjected to rather high vertical accelerations as the drag brakes were activated to decelerate the sled, after reaching peak velocity. The axial deceleration of the sled is of the order of 50 g's.

B. Run No. 2 (7RB1)

The rain damage exhibited by the radome from Run No. 2 (400 feet of rain) suggested that rain erosion should not be a serious problem. Although each drop appeared to cause some surface damage it did not appear to extend significantly beneath the glazed surface. However, from work carried out in developing the shotgun test to simulate Mach 5 rain erosion 4/ it was observed that once the impact pressure was sufficient to cause damage in the flame glazed surface, the damage to the flame glazed surface was more severe than to the unglazed surface. This appeared to be due to the fact that the damage in the glazed surface extended through the glaze with a tendency to chip out a portion of the glaze extending beyond the actual area of impact. In the unglazed surface the damage area was restricted to the area of impact. From this first run in the rain it was felt that better performance would probably have been obtained with an unglazed radome.

C. Run No. 3 (7RC1)

The surface damage caused by the 800 foot rain field in Run No. 3 was as expected from the 400 foot run. It was first assumed that the tip of the radome was lost in the rain or just as the radome emerged from the rain. This would be at the time of maximum vibration. From Figure 16 it was noted that the radome was still in one piece after leaving the rain field, and had therefore, survived the vibration associated with the peak velocity. The next point of high acceleration would be upon sled impact with the water brake. A search of this area uncovered the tip about 800 feet from the point of water brake impact. This suggested that the tip of the radome was essentially pulled away from the rest of the radome. Examination of the radome revealed that the wall thickness in the area of failure was between 0.305 and 0.350 inch. This was only one-half the thickness of the radome just 4 inches aft of this area. For some unexplained reason the wall thickness tapered uniformily from about 0.600 inches at a point about 9 inches from the base of the radome to about 0.300 inches at a point 13 inches from the base. After determining these facts, it was surprising that the radome survived the vibration associated with the peak velocity and the accompanying rain impact. One further observation was made at the track. The slippers on the sled for this run were exceptionally tight. It was only with a great deal of effort that the track crew was able to get the sled on the track. If this tight fit reduced the sled vibration it might explain why the radome survived the maximum velocity through the rain.

D. Run No. 4 (7RD1)

Run No. 4 provided very encouraging data. First, the rain rate was about 3.6 inches per hour. This was due to a cross wind of about 3 knots. Therefore, this run was equivalent to almost 3000 feet at a rain rate of 2-1/2 inches per hour. Although the surface exhibited rather general erosion, the most severe area seemed to be restricted to the area from about 4 inches behind the metal tip to the tip itself. Boresight measurements indicated no measurable effect due to this erosion. The area of most severe erosion revealed that patches of glaze were being removed. This would suggest that further rain impact would intensify local areas of damage and weaken the radome structurally. Such localized areas of damage could act as stress risers and serve as failure sites under the mechanical stresses associated with high levels of vibration which would be expected to be a maximum in this same area.

E. Run No. 5 (7RE1)

An examination of the data from Run No. 5 indicated that the radome broke up after about 2000 feet of rain. Image motion camera photographs (Figures 19, 20, and 21) show that the point of failure occurred while the drag brakes were being activated. This would probably be near the point of maximum lateral acceleration and coincident with the maximum axial deceleration of about 50 g's. From the pieces of the radome (Figure 24) which were found in the area of the broken shower head, two observations could be made: (1) there was no glazed surface remaining on these pieces, and (2) the fracture pattern in the wall of the radome was somewhat columnar from the surface to a distance of about 0.200-inch, and conchoidal below this depth. The absence of the glaze would suggest: (1) a condition of erosion more severe than Run No. 4, (2) that the glaze was not as adherent as in the previous case, and/or (3) that exceptionally high levels of vibration removed the damaged glaze from the radome. The fracture pattern for Figure 24 would suggest that some subsurface damage had occurred.

However, it is estimated that damage was only significant with respect to the vibrational loads associated with the sled trajectory and not significant with respect to an actual missile flight situation.

F. Run No. 6 (7RE2A)

From a study of the data from Run No. 6 it was concluded that the behavior of this dome was essentially the same as Run No. 5. One point was noted about the sled before this run that was not checked before Run No. 5. That is, the slippers fit very loosely. There was at least a 0.25-inch clearance between the slipper and the track. This loose fit on the track would allow for an unusually large initial amplitude of vibration which might continue into the maximum velocity region of the trajectory.

From the vibration data supplied by General Dynamics/Pomona, it was noted that there was an amplification factor between the value for the radial acceleration measured at the base of the dome, and that measured at the tip. At a level of 40 g's input at the base, an acceleration of 283 g's was measured on the radome about 3 inches from the tip, and 625 g's on the tip. In general the vibrational level measured on the body of the radome near the tip was 7 to 14 times the value at the base, and the tip provided a value 16 to 18 times as high as the base.

G. Run No. 7 (7RF2)

The collision of the radome sled with a bird after passing through the rain field was unfortunate in that it prevented a comparison of the boresight patterns before and after rain erosion. However, a comparison of rain erosion damage on the glazed and unglazed radomes was still possible because the tip and front 4 inches of the radome from Run No. 7 (7RF2) was found intact. The rain erosion on the glazed radome from Run No. 4 (7RD1) which was also through 2000 feet of rain was rather general but the most severe erosion was restricted to the area from about 4 inches behind the metal tip to the tip itself.

Both Run No. 4 and Run No. 7 were through 2000 feet of rain at a rate of 2-1/2 inches per hour and both runs had a cross wind of 3 knots which gives an equivalent rain rate of 3.6 inches per hour. Therefore, both runs were equivalent to almost 3000 feet at a rain rate of 2-1/2 inches per hour on the track. This would be equivalent to almost 4000 feet of natural rain at 2-1/2 inches per hour. The conditions for Run No. 7 were somewhat more severe than on Run No. 4 because Run No. 7 reached a maximum velocity of 5430 ft/sec and run No. 4 5100 ft/sec.

A comparison of the rain erosion on the glazed radome and unglazed radome tip section for a distance of 4 inches behind the metal tip indicated the damage to the glazed radome was generally more severe than was the damage on the unglazed radome. There were two large pits, apparently caused by multiple impacts, within 1-inch of the tip on the unglazed radome but these impacts were not more severe than impacts in the same area on the glazed radome. Beyond a distance of 1-inch from the tip the rain erosion on the unglazed radome was very slight and required close visual examination to detect.

These results bear out the results from the Georgia Tech developed shotgun screening test to simulate Mach 5 rain erosion 4/. That is, once the impact pressure was sufficient to cause damage in the flame glazed surface, the damage to the flame glazed surface was more severe than to the unglazed surface. This appeared to be due to the fact that the damage in the glazed surface extended through the glaze with a tendency to chip out a portion of the glaze extending beyond the actual area of impact.

VIII. CONCLUSIONS

From the data obtained for the six rain erosion sled tests described in this report, several conclusions may be drawn concerning the rain erosion resistance of these flame glazed slip-cast fused silica radomes at Mach 5.

1. Rain at velocities above 5000 feet per second does cause surface damage to flame glazed slip-cast fused silica radomes. This damage may be more than superficial, particularly in the presence of high lateral vibrations, and in areas near the tip of the radome.

2. Rain at velocities above 5000 feet per second causes surface damage to unglazed slip-cast fused silica radomes. However, this damage is much less severe than the damage to flame glazed slip-cast fused silica under the same conditions. Also, the stress conditions within the silica wall may be less for the unglazed silica.

3. The lateral vibration near the forward section of the radome may be 7 to 14 times the value measured at the base of the radome. Since the base of the radome extends about 6 inches beyond the forward point of the wedge of the sled, it would be expected that there would be some additional amplification between the sled vibration and that at the base of the radome.

4. Both flame glazed and unglazed slip-cast fused silica can survive 2000 feet of rain at a rain rate of 3.6 inches per hour (measured on the Holloman track) at velocities as high as 5400 feet per second. Converting this to 2-1/2 inches per hour of rain on the track should be equivalent to about 2900 feet. To equate this to 2-1/2 inches per

hour of natural rain requires a correction for the difference in terminal velocity of the raindrops in the two environments. This is 18/13 or a factor of 1.38, and would make the distance equivalent to about 4000 feet in 2-1/2 inches per hour of natural rain.

5. The maximum lateral vibration occurs in the forward portion of the radome, coincident with the area of maximum erosion damage. Radomes which have failed in the rain have done so just after the initiation of the drag brakes. At this point a multiaxial stress situation exists. Lateral vibration is near a peak, and axial deceleration reaches a maximum of about 50 g's at this point. This undesirable mechanical situation coupled with the maximum surface erosion in the same area of the radome would suggest an abnormal stress condition, perhaps an order of magnitude more severe than would be expected in flight.

It appears therefore that in these tests, the rain damage is sufficient to weaken the material to the point where the severe mechanical environment is sufficient to destroy the radome. This is not a measure of the amount of rain necessary to defeat the radome in a real missile application. It rather suggests an absolute minimum environment in which glazed slip-cast fused silica radomes would perform satisfactorily in a real flight situation.

IX. RECOMMENDATIONS

In order to determine more realistically the rain erosion resistance of slip-cast fused silica, the following recommendations are made:

1. Run a sled test with unglazed slip-cast fused silica radome of the existing configuration in 4000 feet of rain.

2. Be sure sled slippers provide as accurate and as close a fit to the track as possible.

3. Instrument sled, transition piece, and radome base to telemeter lateral acceleration data during sled run.

4. Modify radome design to provide radome attachment directly to sled. (Eliminate transition piece.)

5. Modify tip design to minimize weight of metal tip.

6. Modify slippers to provide high temperature, high strength steel slippers with replaceable inserts, and lengthen slippers to provide greater contact area.

7. Instrument sled and radome base to telemeter lateral acceleration data during sled run.

8. If data from 7 indicate no significant improvement in sled vibration, modify sled along lines of Sandia design to provide damping for sled vibrations.

The carrying out of these recommendations should minimize the severity of the abnormal mechanical environment and allow for the establishment of the rain erosion resistance of slip-cast fused silica.

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1. Wahl, Norman E., "Investigation of the Phenomena of Rain Erosion at Subsonic and Supersonic Speeds," AFML-TR-65-330, October 1965.

2. Walton, J. D. and Poulos, N. E., "Slip-Cast Fused Silica," ML-TDR-64-195, October 1964.

3. Reynolds, Marcel C., "Rain Measurement and Simulation for Supersonic Erosion Studies," Sandia Corp. Reprint SCR-474, February 1962.

4. Walton, J. D., Jr., Gorton, C. W. and Harris, J. N., "A Hydrosonic Rain Erosion Test Program," Proceedings of the U.S. Air Force-Georgia Tech Symposium on Electromagnetic Windows, Vol. III, Paper No. 8, June 1966.

APPENDIX

PART II

General Dynamics/Pomona Report

CR 6-223-081-001

GENERAL DYNAMICS, Pomona Division

Radome Engineering Group

Pomona, California

FINAL TECHNICAL REPORT

PART II

PROJECT A-925

DEVELOPMENT OF TEST MODELS FOR RAIN EROSION SLED TESTING OF SLIP CAST FUSED SILICA RADOMES

By

B. E. Johnson, Sr. Engineer, Radomes
L. H. Lightfoot, Design Engineer, Microwave
J. B. Samonte, Structures Engineer

Sub-contract - GIT PO #3136-112S
Contract - DA-01-021-AMC-14464(Z)

January, 1967

Performed For

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia

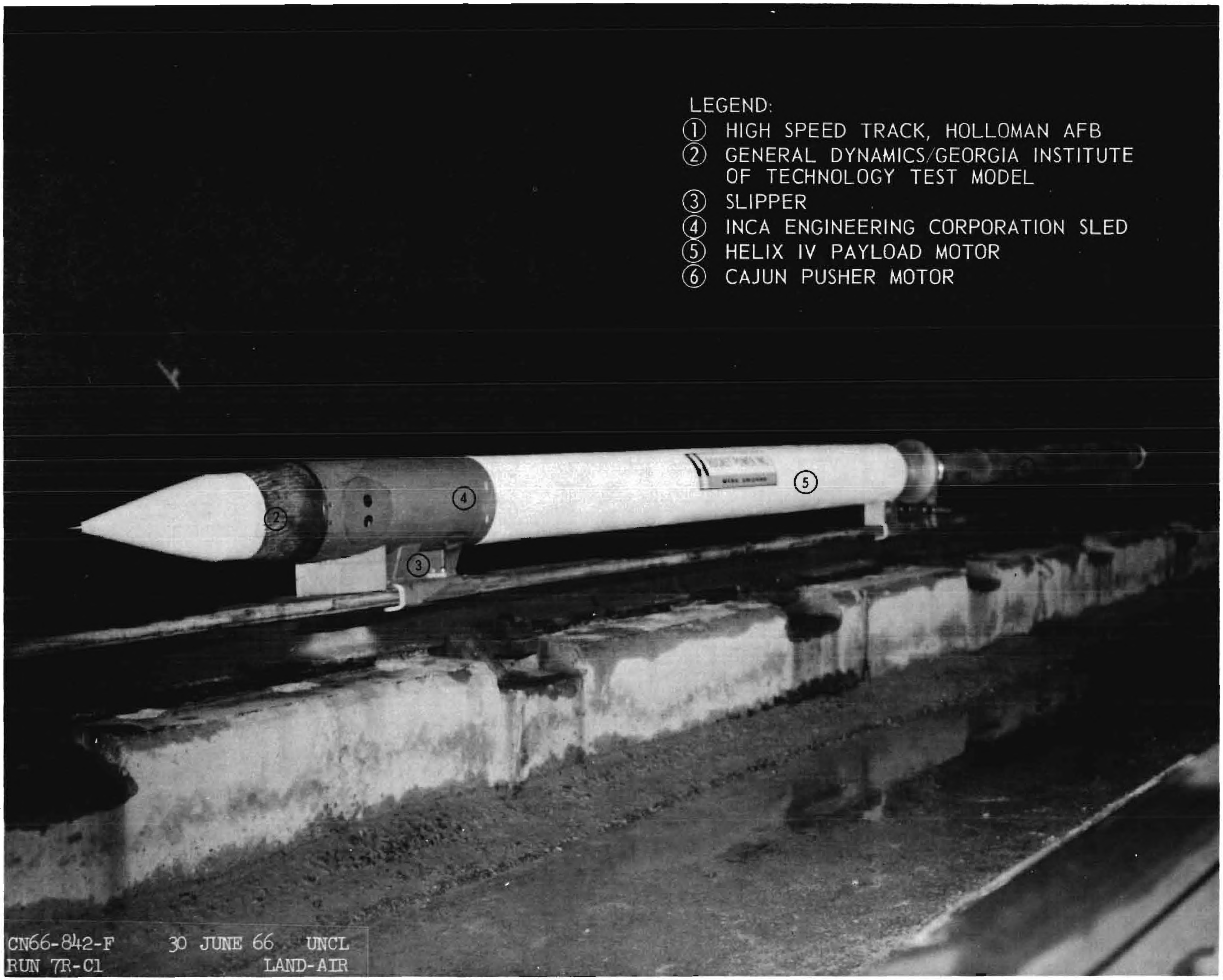

FIGURE 1. FRONTISPIECE

ABSTRACT

This report is Part II to the Georgia Institute of Technology (Georgia Institute) report on the DA-01-021-AMC-14464(Z) program concerned with rain erosion sled testing of slip cast fused silica (SCFS) radomes. Part I summarizes the results of the sled tests conducted at Holloman Air Force Base during the second half of 1966. Part II provides information in regard to the development by the General Dynamics Division in Pomona, California (Pomona Division) of the mach 5 radome sled test model for the Georgia Institute. Radome blanks used by the Pomona Division were fabricated by the Georgia Institute at Atlanta, Georgia.

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ILLUSTRATIONS

Section 1.0

PURPOSE

The purpose of the Georgia Institute Purchase Order #3136-1125 was to subcontract radome structure assembly test model design and fabrication. This subcontract obtained the technical support required to develop and deliver functional test hardware within the brief schedule allotted by the DA-01-021-AMC-14464(Z) test program. The purpose of the program was to study the behavior of slip cast fused silica radomes operated in a rain environment at velocities near mach 5.

Section 2.0

WORK STATEMENT

The Pomona Division of General Dynamics was to develop a test model which would survive high speed sled environments[1] using slip cast fused silica radomes. Development time from work start to first article delivery was to take place during the second quarter of 1966 (three months). Boresight measurements were to be made before and after erosion on those radomes which were intact after testing.

[1] Environments other than rain. Mach 5 rain effects of course were not well understood.

Section 3.0

DESIGN CONSIDERATIONS

The design was required to:

3.1 Use the Georgia Institute furnished radome castings.

3.2 Adapt the 7.50 inch as cast radome base (outside) diameter to a 9.75 inch vehicle (outside) diameter.

3.3 Protect the slip cast fused silica tip from being eroded in the rain.

3.4 Withstand the severe loading caused by the combination of:

(1) aerodynamic heating,

(2) radial vibration of a sled with a rigid suspension system,

(3) acceleration and braking forces, and

(4) aerodynamic lifting loads.

Section 4.0

DESIGN APPROACH

4.1 Test conditions were predicted after all available information in regard to acceleration, velocity, shock and vibration was obtained from Holloman AFB and Inca Engineering (the test vehicle contractor).

4.2 Materials were selected and the configuration was devised to:

(1) Accommodate the mach 5 heating without inducing stress in the radome tip or attachment.

(2) Withstand the mechanical loads resulting from shock, vibration and lifting.

Section 5.0

TEST PLAN

Final acceptance was to include a pre-run vibration test and boresight.

5.1 Vibration Test

Vibrating test was to be accomplished by a 40 g ambient sinusoidal sweep over a 25 to 2500 cps band. This frequency band was swept in 28 seconds. Separate tests were made with the input along and normal to the models longitudinal axis. These tests were made to assure that the model would survive predicted environments (excluding rain). Information obtained from the Holloman track facility and sled contractor was interpreted by the Pomona Division personnel specialized in aerodynamics, structures analysis, thermomechanics and sled structural dynamics. These personnel predicted that

(1) the shock vibration and lifting could be properly simulated by the aforementioned testing, and

(2) the temperature effects would be accommodated by the design,

(3) temperature testing was not required.

5.2 Boresight Test

Electrical evaluation was limited to single frequency vertical polarization boresight measurements. The radomes were crudely tailored to permit the inplane and cross talk error versus look angle plots to stay on the recorder paper. The look angle was ±30 degrees from the domes center line.

Data taken after a run was to be compared to data taken before a run in order to get some idea of the effect erosion had on boresight errors.

Section 6.0

DESIGN DETAILS

6.1 Tip

The metal tip configuration was devised to permit significant differential expansion to occur between the tip and radome apex without inducing stresses in the ceramic or without permitting the tip to become loose, Figures 2 and 3. The tip size was selected to have minimal effect on boresight error. It was machined from Hastelloy X, a commercially available high temperature steel alloy.

6.2 Attachment

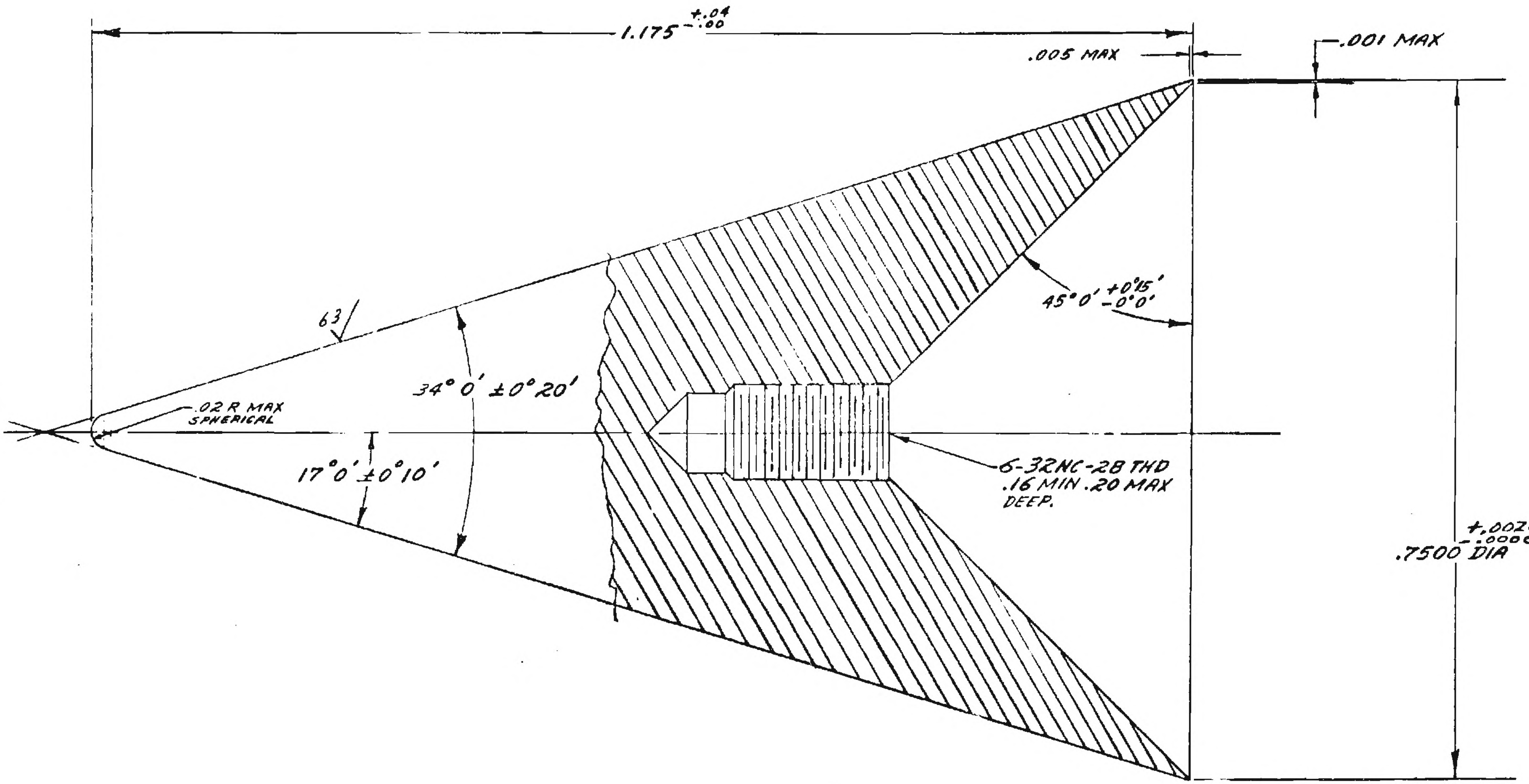
The radome to adapter attachment, Figure 4, was designed to thermally isolate the radome attachment ring, Figure 5, from aerodynamic or motor heating. The attachment ring was made of Invar 36. Invar 36 matches the slip cast fused silica thermal coefficient of expansion from -60°F to 300°F. This temperature range exceeds temperature extremes resulting from processing, transportation or storage environments.

6.3 Assembly of Tip and Ring

Both the tip and ring were carefully fitted to the matching tapers machined on the radomes outer and inner surfaces respectively.

The taper fit between the tip and the radome is maintained by a spring. This design allows the tip to expand and to move along

Figure 2
Page 8



TIP, RADOME

SK223-415

MATERIAL: HASTELLOY ALLOY X PER AMS5754-C

L.H. LICHTFOOT 4-26-66 SCALE 10/1

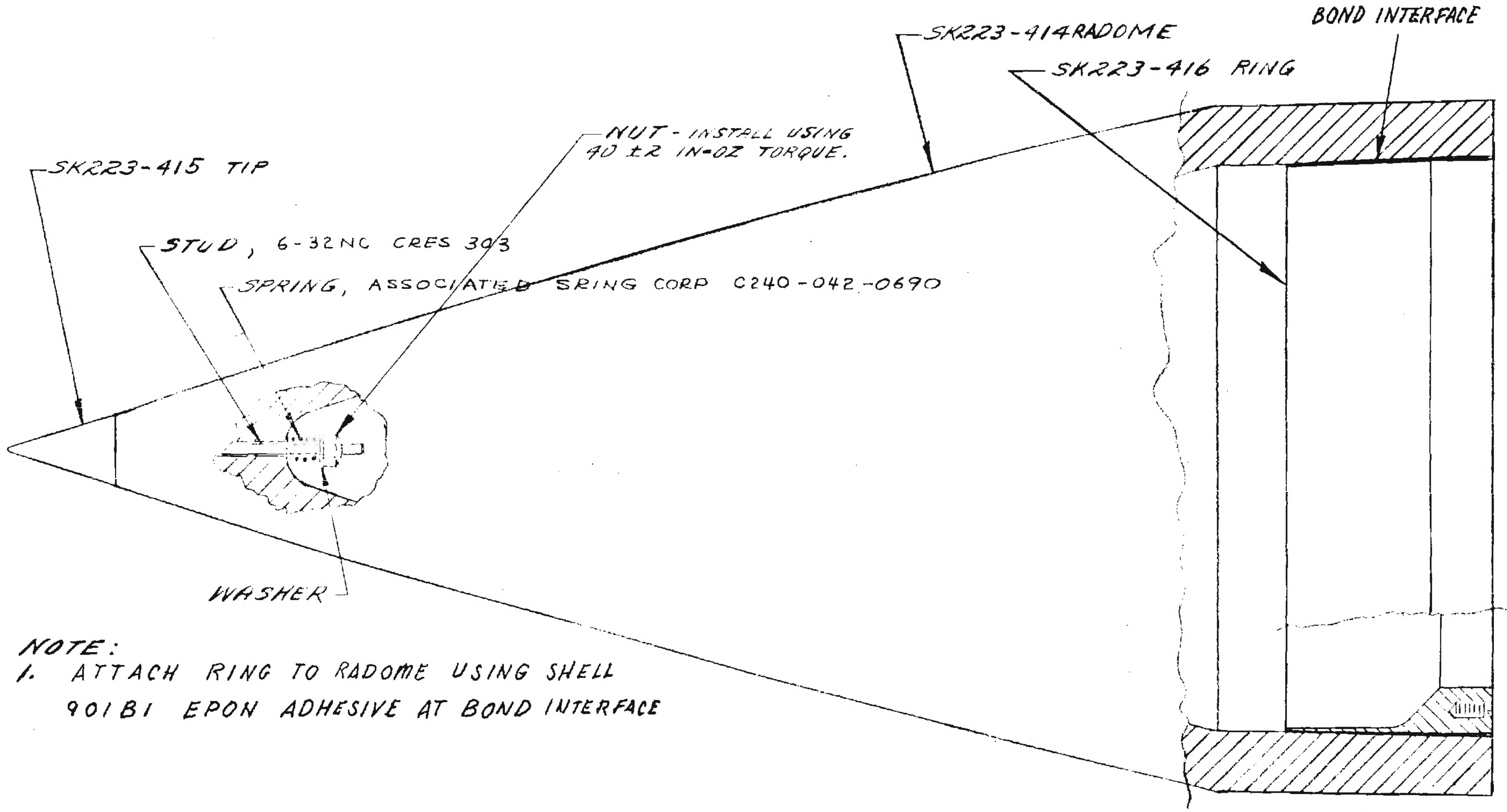


Figure 3
Page 9

L.H. LIGHTFOOT & B.E. JOHNSON

RADOME ASSY

SK223-422

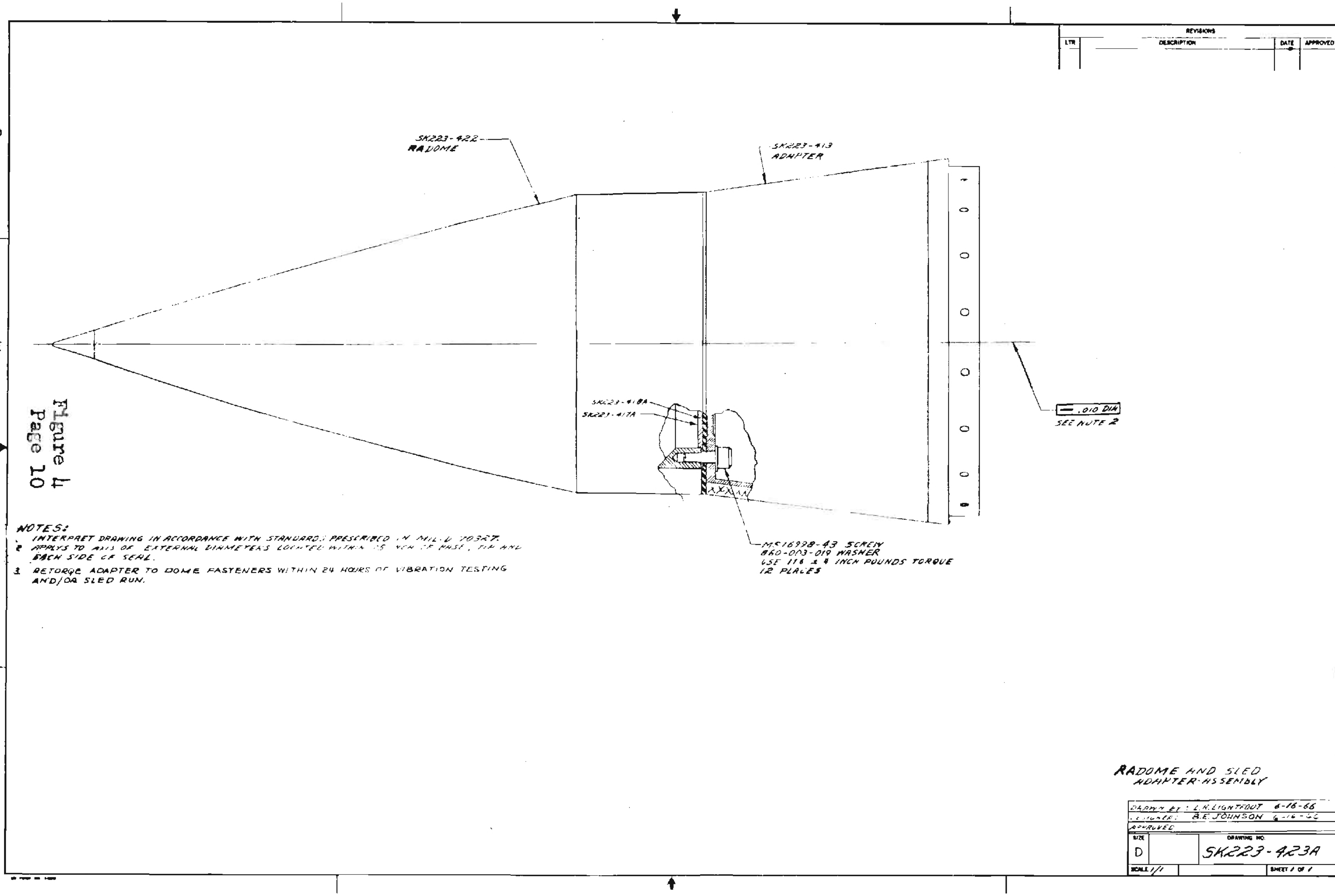


Figure 4
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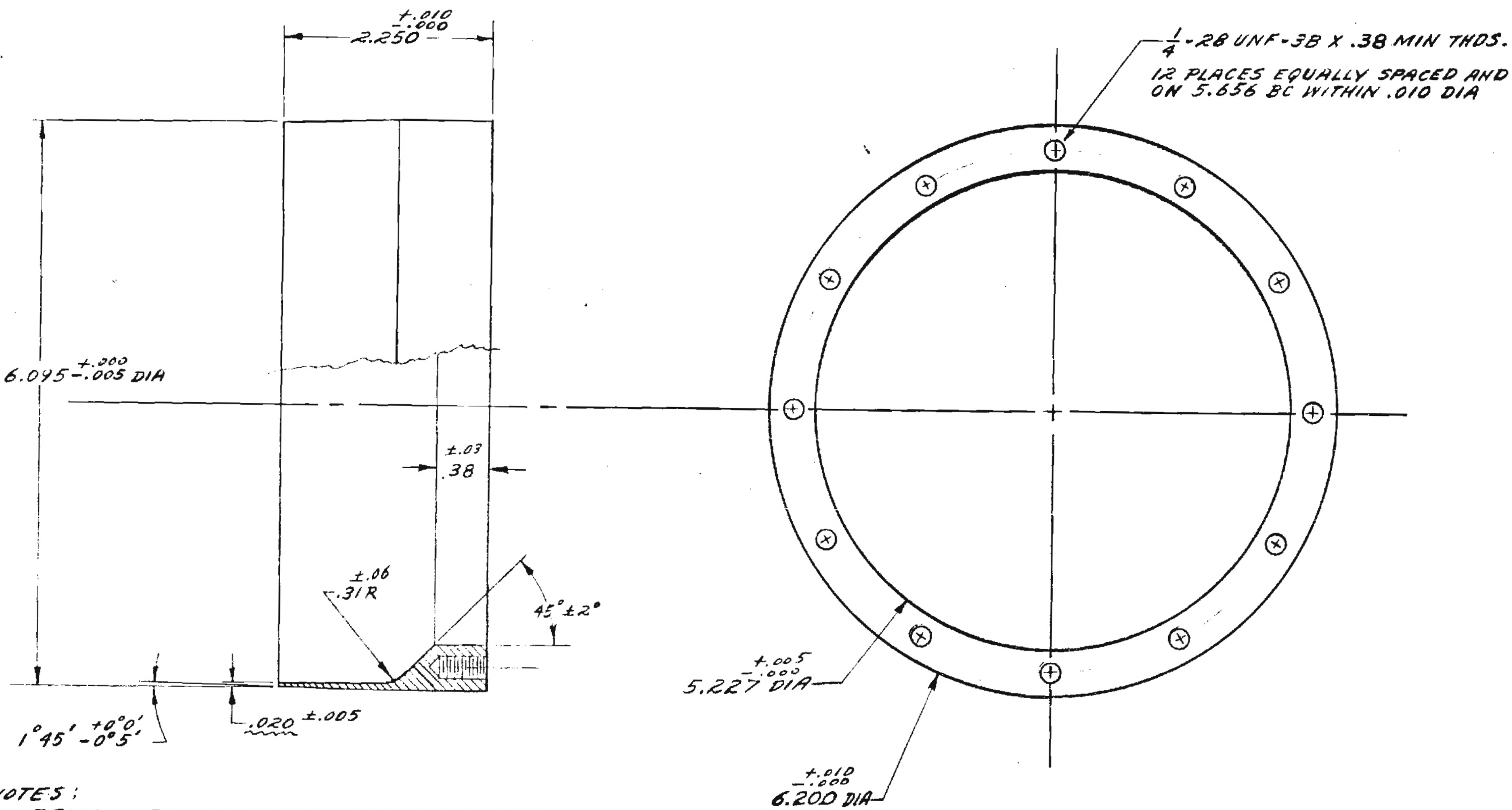

Figure 5
Page 11

NOTES:
1. REMOVE BURRS AND BREAK SHARP EDGES.
2. 125√ ALL OVER

MATERIAL: CARPENTER STEEL CO., READING, PA.
INVAR "36"

L.H. LIGHTFOOT & B.E. JOHNSON

RING, MOUNTING
SK223-416

its taper interface with the radome. (At 2000°F slip cast fused silica has a thermal coefficient of expansion of 0.54 x 10^{-6} inches/inch/degree F while Hastelloy X has a thermal coefficient of expansion of 16.7 x 10^{-6} inches/inch/degree F.

The ring was first primed with 3M EC1290 and cured at 300°F for 1 hour and then bonded to the radome with Shell 901/B-1 adhesive cured for 8 hours at 120°F. (Note that the ring-to-radome bond-line cure temperature was only 40% of the 300°F allowed by matched coefficients of expansion for the Invar and slip cast fused silica.

6.4 Joining the Radome Assembly to the Adapter

The cork gasket, Figures 6 and 9, and the asbestos covering over the adapter (section which provided the transision from the 7.5 inch radome outside diameter to the 9.75 inch braking section outside diameter), Figure 7, thermally isolate the attachment ring from all short duration, high rate heating.

Note in Figures 3 and 9 that the aft end of the radome lies on the same plane as the aft face of the Invar ring. The aluminum disc was designed to allow the radome as well as the ring to support the clamping load. The cork between the disc and the invar ring was loaded to the point where virtually no further compression set could occur. The cork between radome butt end and bulkhead was only partially compressed thereby permitting the radome to provide bearing surface on the adapter bulkhead without the possibility of shearing the Shell 901/B-1

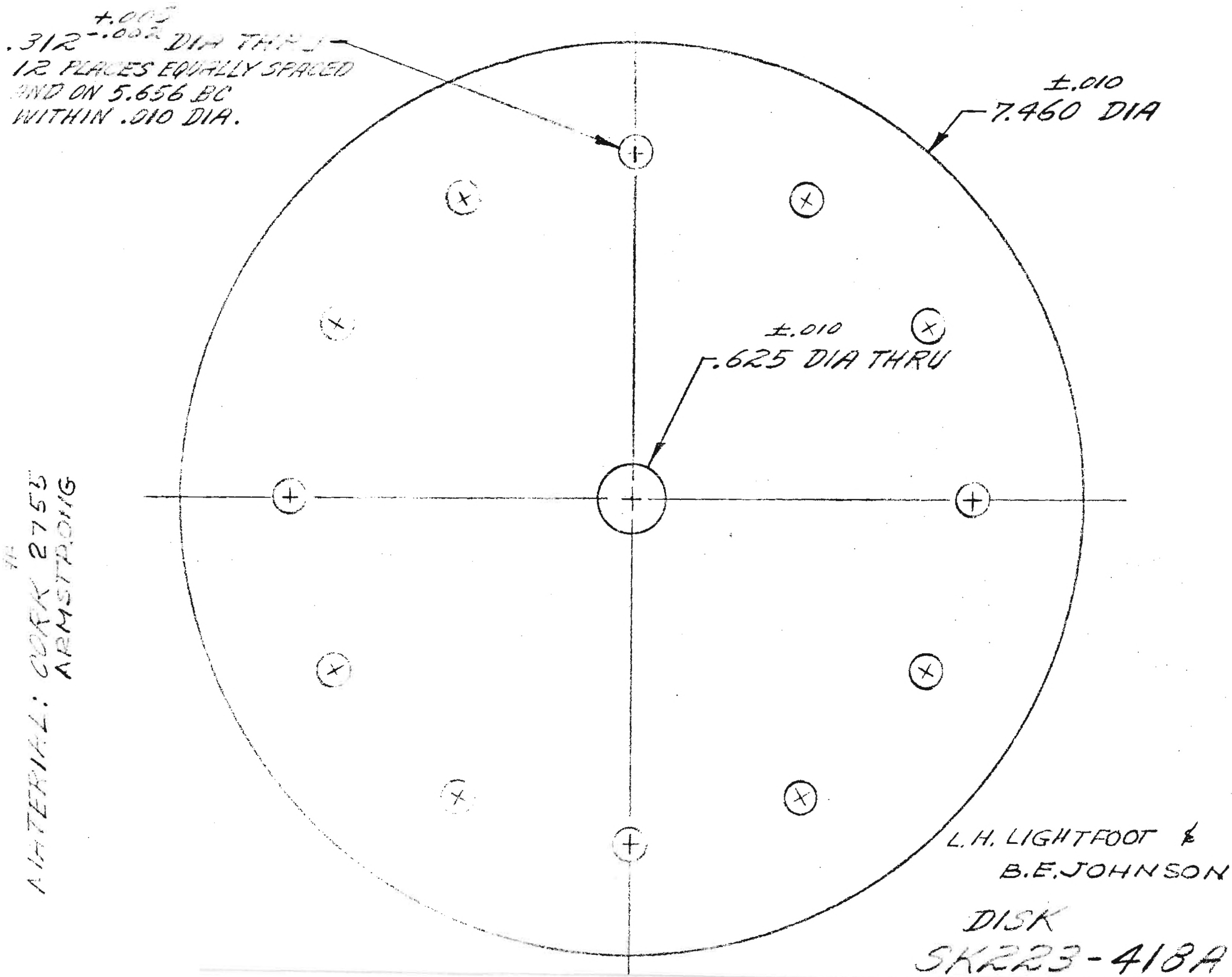

Figure 6
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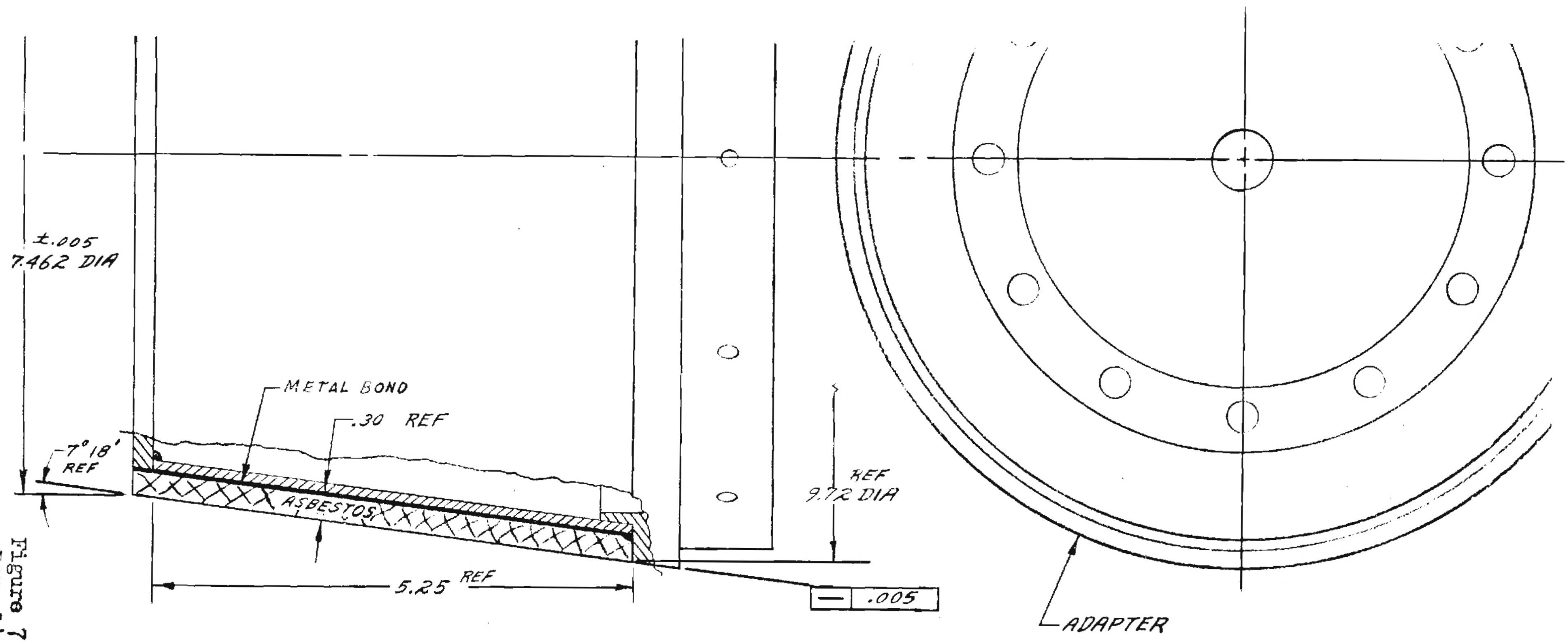


Figure 7

ASBESTOS: U.S. POLYMERIC FM-5076 (CURED AT 400°F & 150 PSIG)

METAL BOND: NARMCO 4021 TYPE II

L. H. LIGHTFOOT & B.E. JOHNSON

RADOME TO SLED ADAPTER ASSY

SKR23-413

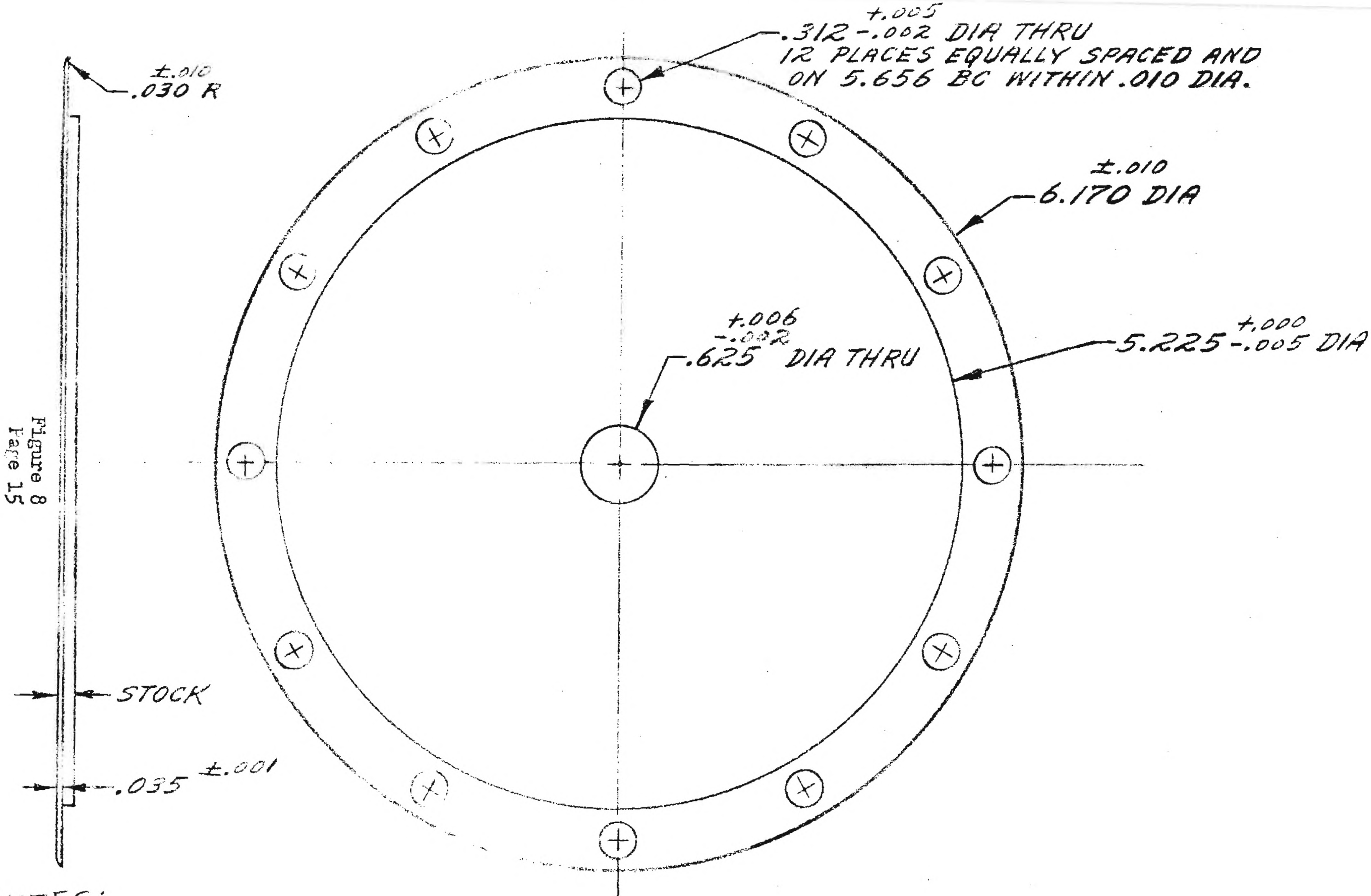


Figure 8
Page 15

NOTES:

1. REMOVE BURRS AND BREAK SHARP EDGES.

L. H. LIGHTFOOT & B. E. JOHNSON

DISK, FORWARD

MATERIAL: 005-012-042
AL ALLOY

SK223-417A

bond. The use of the cork disc decreased the amplification factor (Section 5.1) approximately 20%. This was due to the support afforded the radome to adapter assembly by the radome bearing on the cork. Without the cork there is a gap between the radome and the adapter, Figure 9.

The tip and the adapter fastener torque values were determined during vibration testing. The Radome and Sled Adapter Assembly, Figure 4, was assembled several days before the sled run. Torque values for all fasteners were checked during the 24 hour period immediately prior to test.

Section 7.0

STRUCTURAL ANALYSIS

An analysis was made to determine the structural margins for the design when subjected to the predicted loads. The analysis found the design adequate.

7.1 Summary

In the radome adapter joint, the following results were obtained.

Item	Stress	Margin of Safety
Fused Silica	746 psi tensile	+1.68
Adhesive	1410 psi shear	+0.63

Above stresses and margins of safety were based on a critical combined body load of 14,800 in-lbs bending moment applied at the radome to adapter joint.

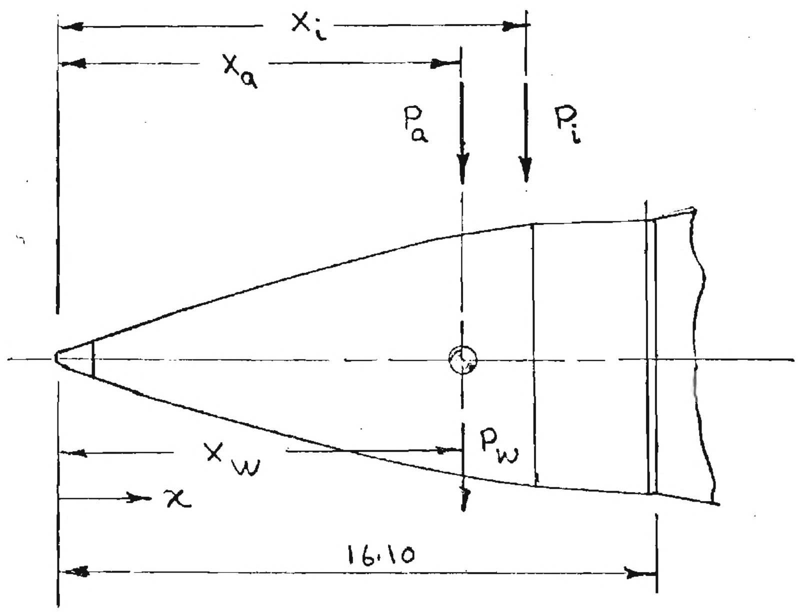
The thermo-mechanical stresses set-up in the tip assembly are so small they were not considered. The machined hole in the radome tip provides enough clearance to accommodate full radial expansion of the metal stud. Sufficient preload is retained by the spring after longitudinal thermal expansion of the stud has occurred.

Preliminary investigation showed that the 12 (MS 16998-43) screws were not over stressed by the 116 ± 4 in-lbs torque.

7.2 Details of Analysis

A. The most severe loads on the model during the sled test result from lifting and vibration.

The Aerodynamics and Dynamics Groups were consulted to establish the predicted loading conditions. The following loads were used in the stress analysis of the radome assembly:



Loads

P_i = 1100 lbs; X_i = 12.60 in. at M = 5.0

P_a = 1800 lbs; X_a = 10.75 in. at M = 5.0

P_w = 240 lbs; X_w = 10.75 in. during all sled test regimes.

Where

P_i = The net lifting load due to shock reflection interference at Mach 5.0.

P_a = The net lateral aerodynamic load induced due to a 3.0° angle of attack.

P_w = Body force based on 12.0 lbs radome weight at 20 g's lateral acceleration.

X_i, X_a, X_w = Line of action position for P_i, P_a, P_w respectively.

Call M, V the net bending and shear at X = 16.10 inches.

$$M = \sum_{j = i,a,w} P_j \, (16.10 - X_j); \quad V = \sum_{j = i,a,w} P_j$$

Subscript	P_j, lbs	X_j, in	$(16.10-X_j)$ in.	$P_j(16.10-X_j)$ in-lbs.
i	1100	12.60	3.50	3850
a	1800	10.75	5.35	9630
w	240	10.75	5.35	1284
	V=3140 lbs			14,764 in-lbs

M ≈ 14,800 in-lbs.

B. Stresses In Radome Assembly

Stresses in the radome assembly will be due to aerodynamic and vibratory loads determined in the previous section (loads).

Thermal stresses will not be included in the analysis because they are negligible. Inspection of the radome assembly shows that the radome adapter joint is adequately insulated from external aerodynamic heating. The assembly configuration of the tip is designed to accommodate the differential thermal expansion that will occur between the metal tip and the slip cast fused silica radome end. The exposed area of the fused silica radome should not be stressed significantly due to excellent thermal shock property of slip cast fused silica.

Two areas of the assembly were considered; the radome-adapter joint and the tip assembly.

(a) Radome-Adapter Joint

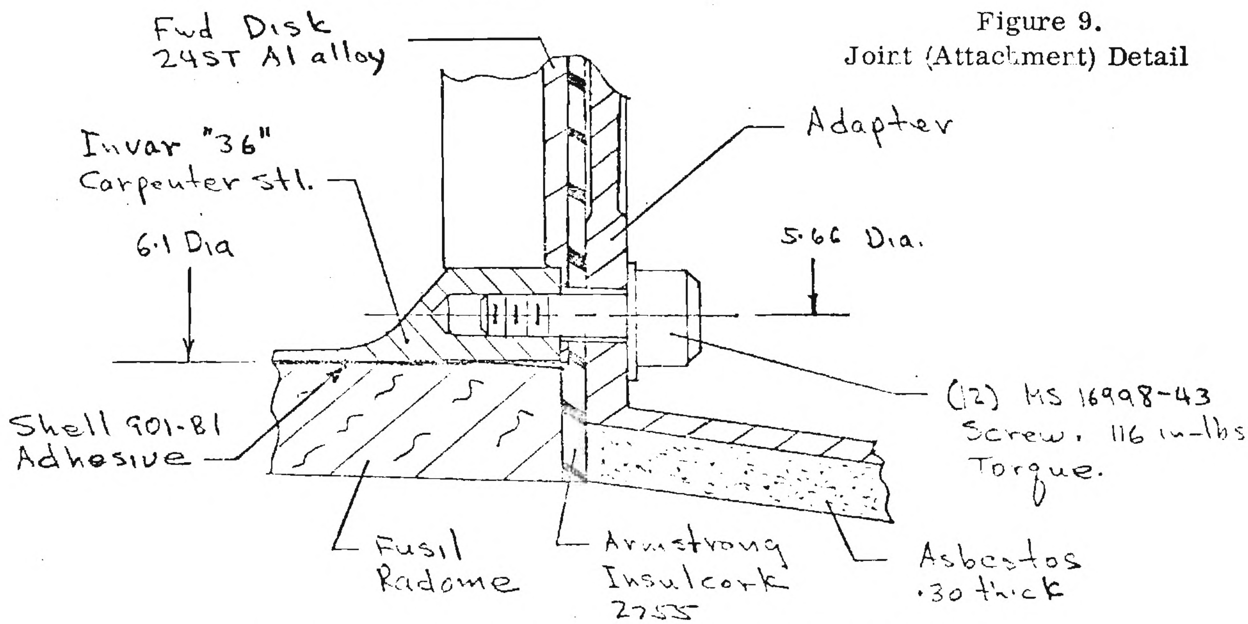


Figure 9.
Joint (Attachment) Detail

Let q_m = Longitudinal load on bondline due to bending moment M.

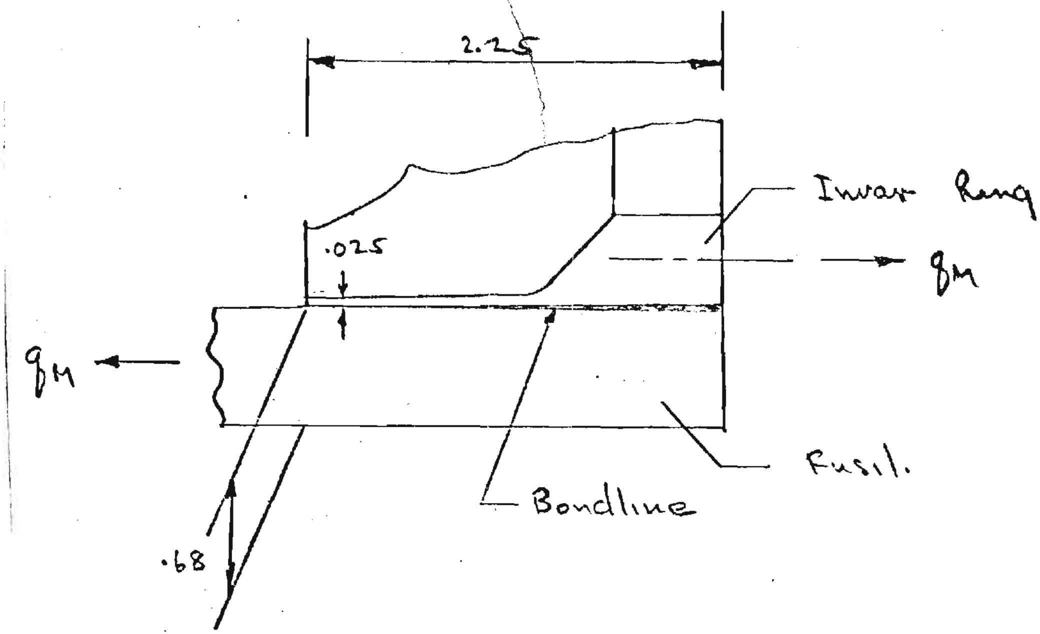
$$q_m = \frac{M}{\pi R^2}$$

$$M = 14{,}800 \text{ in-lbs}$$

$$R = \tfrac{1}{2}(6.1) = 3.05 \text{ in}$$

$$q_m = \frac{14{,}800}{\pi (3.05)^2} = 506 \text{ lb/in}$$

BONDLINE - Between Invar Ring and Radome.



Invar Ring/Radome

(1) Tensile Stress - Slip Cast Fused Silica Radome

$f_t = \frac{q_m}{t_f}$

$q_m = 506$ lb/in

$t_f = .68$ in

$f_t = \frac{506}{.68} = 746$ psi

$F_{allow} \approx 2000$ psi tension

Allowable is conservatively estimated. Modulus of rupture tests on material show average value of 4000 psi.

$$MS = \frac{F_{allow.}}{f_t} - 1$$ Margin of safety -(Tension)

$$MS = \frac{2000}{746} - 1 = +1.68 \text{ (Adequate)}$$

(2) Shear Stress-Bond Interface

$$f_{s_{max}} = f_{s_{ave}} \left[\left(\frac{\Delta}{w}\right)^{\frac{1}{2}} \left(\frac{w - 1 + \cosh \sqrt{w\Delta}}{\sinh \sqrt{w\Delta}} \right) \right]$$

(Reference Prod. Engineering, 7 July 1958, Page 64)

$$f_{s_{ave}} = \frac{9m}{L}$$

$$\Delta = \frac{3}{8} \frac{E_a L^2}{E_2 t_2 d}$$

$$w = \frac{E_1 t_1 + E_2 t_2}{E_2 t_2}$$

$E_2 \geq E_1$

E_a = Adhesive modulus

E_2 = Invar ring modulus

E_1 = Fusil modulus

d = Bond thickness

L = Bond length

t_1 = Radome thickness

t_2 = Ring thickness

$E_a = 3 \times 10^5$ psi (901/B-1 Adhesive)

$E_2 = 20.5 \times 10^6$ psi

$E_1 = 3.5 \times 10^6$ psi

L = 2.25 in

d = .005 in min

t_1 = 0.68 in

t_2 = .025 in

$$w = \frac{(3.5)(.68) + (20.5)(.025)}{(20.5)(.025)} = 5.64$$

$$\Delta = \frac{3}{8} \; \frac{3 \times 10^5 (225)^2}{(20.5 \times 10^6)(.025)(.005)} = 222$$

$$f_{s_{ave}} = \frac{506}{2.25} = 225 \text{ psi}$$

$$f_{s_{max}} = 225 \left[\left(\frac{222}{5.64}\right)^{\frac{1}{2}} \left(\frac{5.64 - 1 + \cosh \sqrt{(5.64)(222)}}{\sinh \sqrt{(5.64)(222)}} \right) \right]$$

$$f_{s_{max}} = (225)(6.28) = 1410 \text{ psi}$$

Material: 901/B-1 Epon Adhesive

Shell Chemical Co.

F_{su} = 2,300 psi (Based on cure temperature of 150°F at one hour exposure. Ultimate value is at 150°F environment.)

$$MS = \frac{F_{su}}{f_{s_{max}}} - 1 \qquad \text{Margin of safety}$$

$$MS = \frac{2300}{1410} - 1 = +0.63$$

(b) Tip Assembly

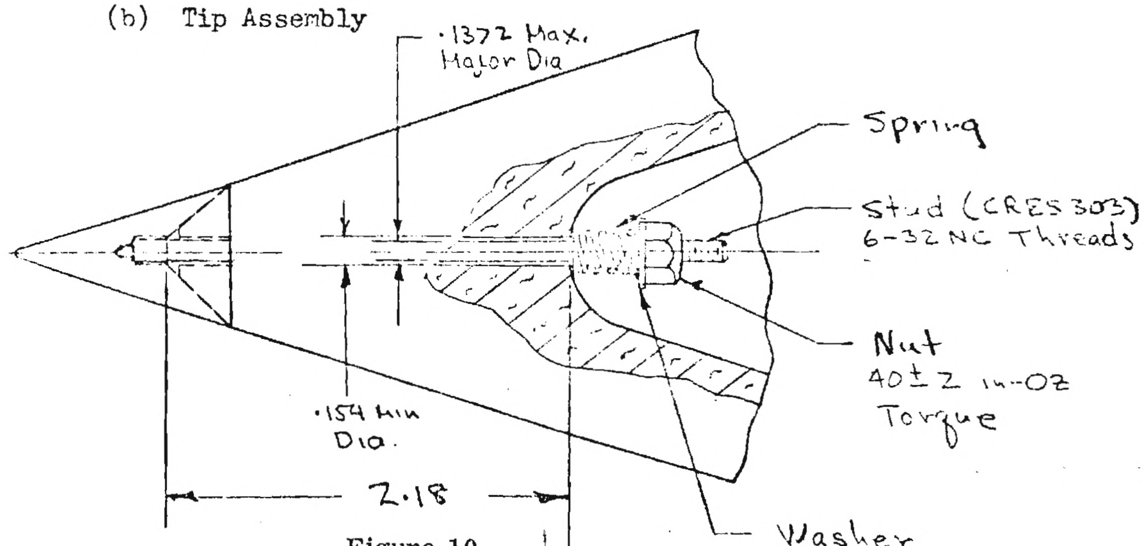


Figure 10.
Tip Assembly Detail

Spring Data:

Associated Spring Corporation C240-042-0690

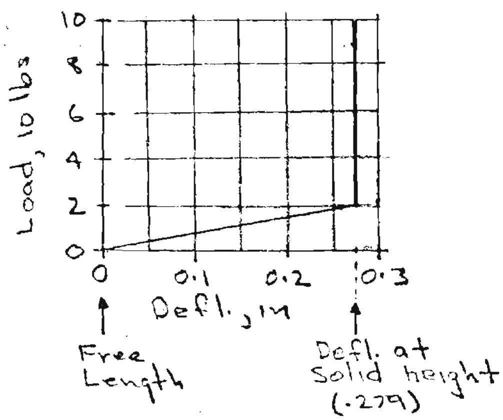
O.D. = .240 in.

Wire Diameter = .042 in

Free Length = 0.69 in

Solid height = 0.411 in

Spring rate = 75.0 lb/in



Tip Spring, Load Deflection

Let P_p = Maximum load on spring due to torque T_w.

$P_p = K_p T_w$

T_w = 40 ± 2 in-oz = 42 in-oz max. (2.62 in-lbs.)

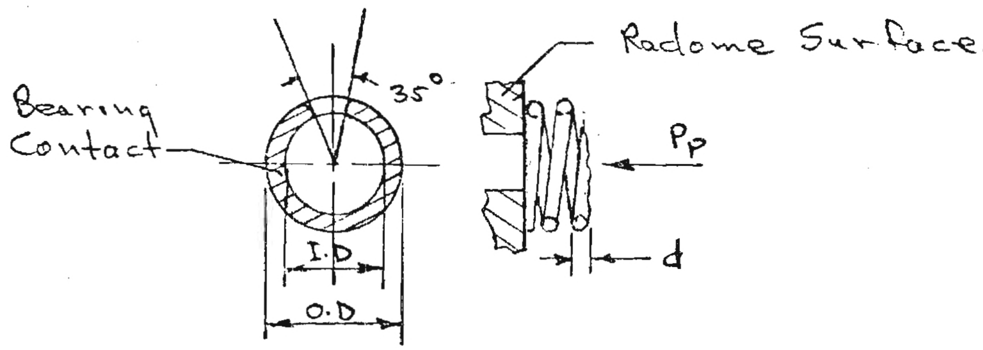
K_p = 34 lbs/in-lbs. for a 6-32 NC thread steel screw-steel nut.

(Reference Prod. Engineering, November 1943)

P_p = (34)(2.62) = 89.2 lbs.

From the spring load-deflection curve, shown above, the spring is compressed to its solid height.

(3) Bearing Stress - Spring on Radome Surface



Spring Bearing Detail

$$f_{br} = \frac{P_p}{A_{br}}$$

$P_p = 89.2$ lbs

$$A_{br} = \frac{\pi}{4} (\overline{O.D.}^2 - \overline{I.D.}^2) \left(\frac{360° - 35°}{360°}\right)$$

O.D. = .240 in

I.D. = O.D. - 2d = .240 - 2(.042) = .156 in

$$A_{br} = \frac{\pi}{4} (\overline{.240}^2 - \overline{.156}^2)\left(\frac{325}{360}\right) = .0236 \text{ in}^2$$

$$f_{br} = \frac{89.2 \text{ lbs}}{.0236 \text{ in}^2} = 3780 \text{ psi (low)}$$

The compressive allowable strength of fused silica is about 20,000 psi.

(4) Thermal Expansion of the Metal Stud

$E_T = \alpha (T - T_o)$

E_T = Thermal Strain

α = Coefficient Thermal expansion

$\alpha = 10.4 \times 10^{-6}$ in/in for CRES 303 ($32° \leq T \leq 1200°F$)

(Reference Republic Stainless Steel Hdbk.)

$T = 1000°F$ (Assumed)

$T_o = 100°F$ base temperature

$\epsilon_T = 10.4 \times 10^{-6} (1000 - 100) = .00935$

(a) Diametrical Expansion ($\Delta_{O.D.}$)

$\Delta_{O.D.} = \overline{O.D.} \; \epsilon_T$

$\overline{O.D.} = .1372$ in

$\Delta_{O.D.} = (.1372)(.00935) = .00128$ in

The new O.D. becomes $.1372 + .00128 = .1385$ in.

If the new O.D. of the stud is compared with the O.D. of the radome hole, $.1385 < .154$ min. = I.D. radome hole. No thermo-mechanical stress is set-up between radome and stud.

(b) Longitudinal Expansion (Δ_L)

$\Delta_L = L \; \epsilon_T$

$\Delta_L = 2.18$ in. (Tip Assembly Sketch)

$\Delta_L = (2.18)(.00935) = .0204$ in.

From the load-deflection curve of the spring, this expansion reduces the preload on spring to approximately 20 lbs. It is noted that the amount of preload reduction may be more than computed because the spring rate is decreased with temperature increase. However, the spring is located farthest back of assembly so that actual temperature which it will experience is much smaller than average stud temperature assumed.

The preceeding discussion shows that no thermo-mechanical stress will occur between radome and stud (diametrically) and that sufficient preload on the spring is retained after longitudinal thermal expansion of the stud has occurred.

Section 8.0

INSPECTION

8.1 Slip Cast Fused Silica Blanks

Each radome blank was carefully inspected before machining. The best units were selected. Discrepant units were scrapped.

8.2 Bulkhead

The forward machined bulkhead surface was inspected and found to be to print requirements in regard to flatness and parallelism to the adapter base.

8.3 Cork

The cork sheeting was inspected and found to be .080 ± .003 inches thick. Compression set measurements made on 1 inch square coupons cut from the cork were found to be consistent within ± 6%. (Figure 11 shows a typical plot.)

8.4 Disc

The aluminum discs were inspected and found to be to drawing machining tolerances.

8.5 Other Parts

All other parts were assembly fit checked.

8.6 Final Assembly

The final assemblies were inspected and found to comply with concentricity and fastener torque values specified on Figures 3 and 4.

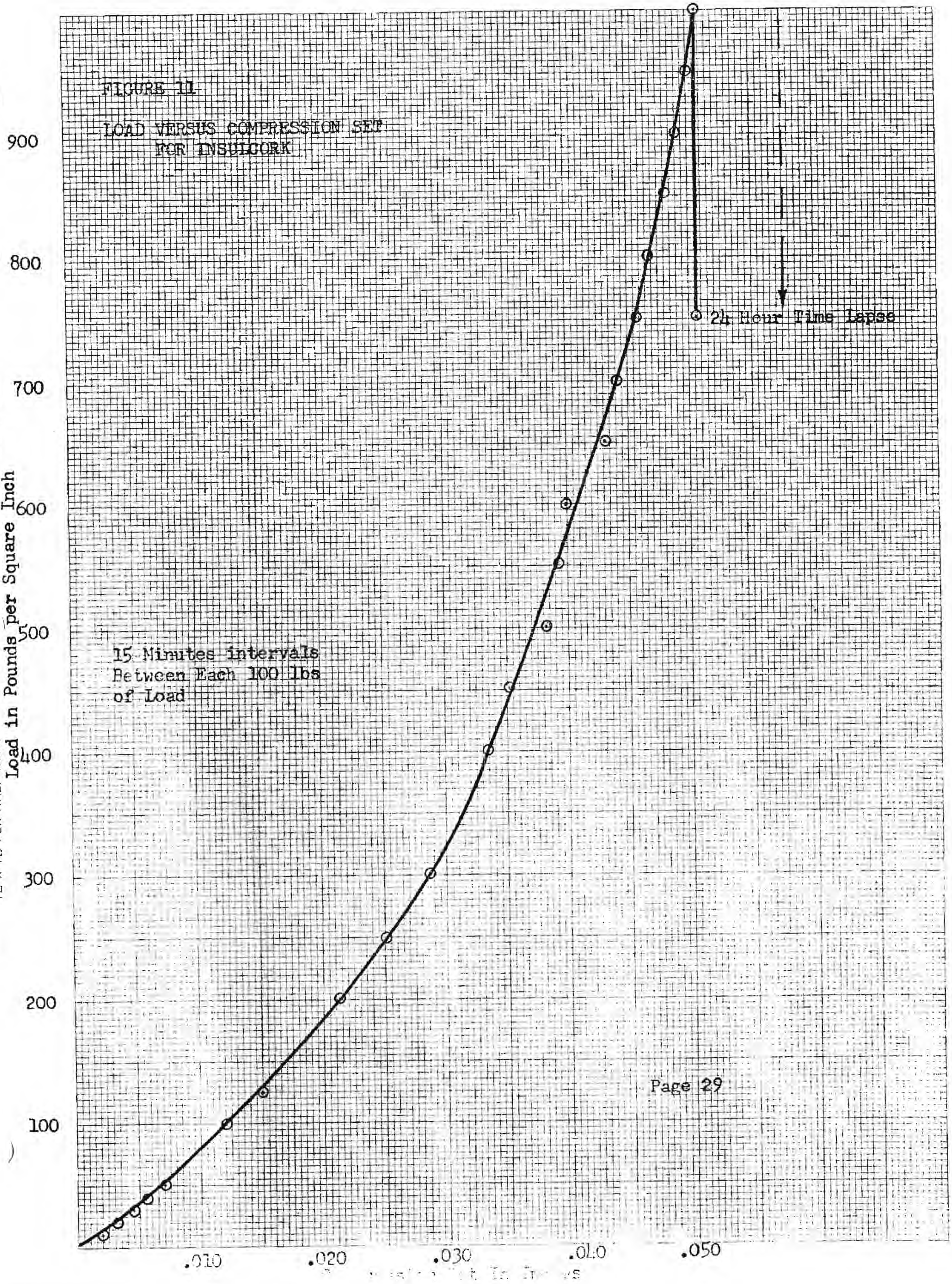


FIGURE 11
LOAD VERSUS COMPRESSION SET
FOR INSULCORK
24 Hour Time Lapse
15 Minutes intervals
Between Each 100 lbs
of Load
Load in Pounds per Square Inch
900
800
700
600
500
400
300
200
100
.010
.020
.030
.040
.050

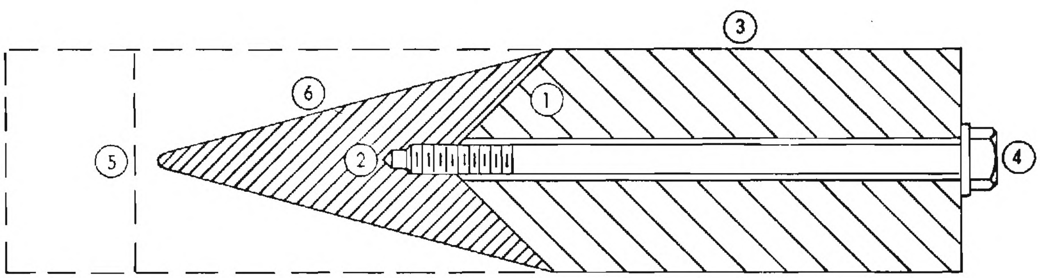
Section 9.0

MACHINING AND TOOLING

Parts were fabricated in a lot of 7 sets. The order in which each operation occurred is indicated by the sequence of the numbers on the following narratives:

9.1 Tip

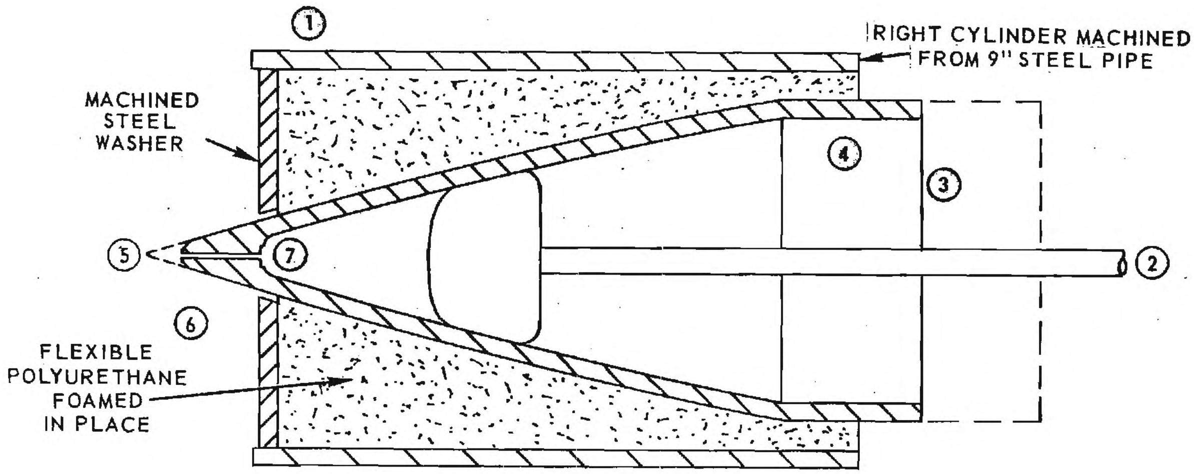
The 5/8 inch diameter Hastelloy X rod was chucked in a screw machine. Surface (1) was turned. The hole (2) was drilled and tapped. A tapered tip holding tool (3) was made to hold the part on surface (1) by means of a 6-32NC bolt (4) which passed through an oversize hole in the holding tool. The Hastelloy rod was cut off at (5) approximately 2 inches forward of the intersection of surface (1) with its (3). The tapered holding tool (3) was chucked in a lathe and surface (6) was machined. The fastener (4) and holding tool (3) were then removed.



TIP MACHINING FIXTURE & SEQUENCE

9.2 Radome

A radome holding fixture was fabricated so that the radome could be machined.



RADOME GRINDING FIXTURE & SEQUENCE

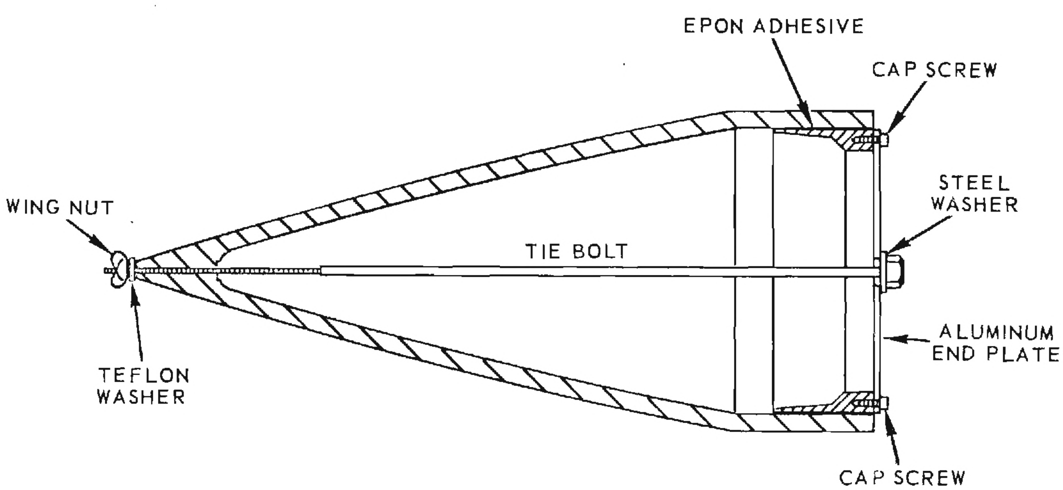
With the holding tool chucked at (1) the radome was forced into the holding tool by a contoured soft wood knob glued to a broomstick (2) which was held in the lathe tailstock. The aft cut off (3) was made, the ring bonding (interface) taper (4) was ground. Then the broomstick was removed from the radome. The holding tool was removed from the chuck, turned around and chucked at the radome cut off end with the radome cutoff bottomed out on a hard rubber pad. The apex (5) of the dome was cut off; the through hole (6) was bored; and, the external taper (5) was machined. The holding tool was removed from the lathe so the spot face (7) could be ground.

9.3 Ring, Gasket, Adapter and Disc

Information regarding the fabrication of the ring, gasket, adapter and disc is provided on the drawings for these parts, Figures 5, 6, 7 and 8, respectively.

9.4 Ring to Radome Bonding Tooling

The ring bonding tooling, shown below, held the aft end of the ring and the radome on a common plane during cure of the Shell 901/B-1 epon adhesive.



RING BONDING FIXTURE

Section 10.0

MECHANICAL AND ELECTRICAL TESTING

10.1 Vibration Testing

Vibration tests were made per Section 5.1. The test models survived.

The amount that the vibration input was amplified was different for each test model. This is believed to be due to the fact that each radome had its particular variation in wall thicknesses with the accompanying differences in weight, weight center and body modes. But for each assembly the amplification and frequency at which amplification occurred remained consistent at any g level input, I, up to the 40 g level test limit.

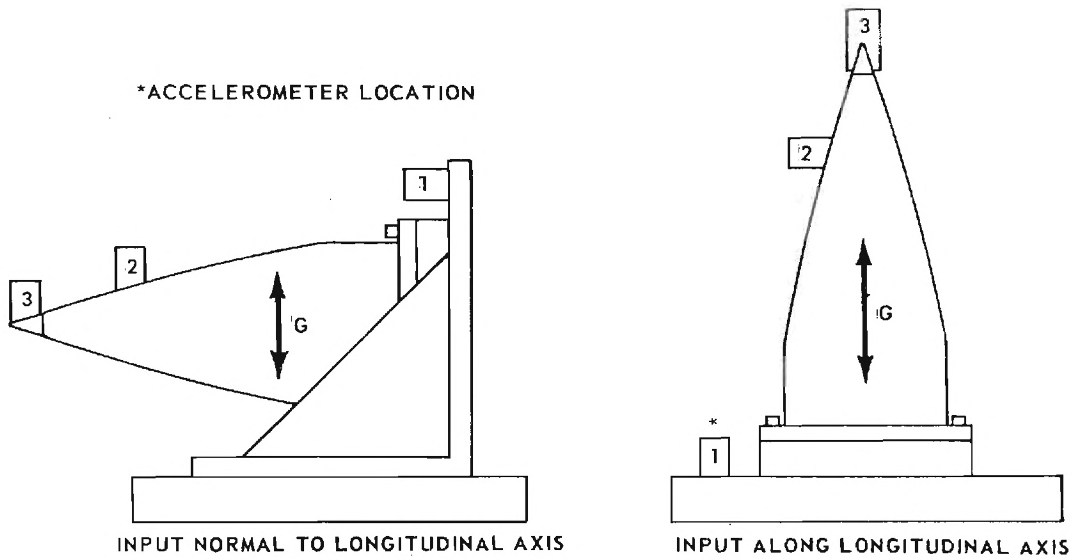
The vibration data for the unit radome assembly which was thought to be most representative is summarized below:

I = input

DIRECTION * OF INPUT	FREQ. (cps)	LOCATION OF ACCELEROMETER 1	2	3
LONGITUDINAL				
Longitudinal Axis	900	I	1 x I	1 x I
	1500	I	1 x I	2 x I
	2000	I	2 x I	6 x I
	2500	I	4 x I	12 x I
LATERAL				
Normal to Longitudinal Axis	375	I	2.5 x I	16 x I
	750	I	3 x I	18 x I

*See input diagrams at top of page 34.

Load Input

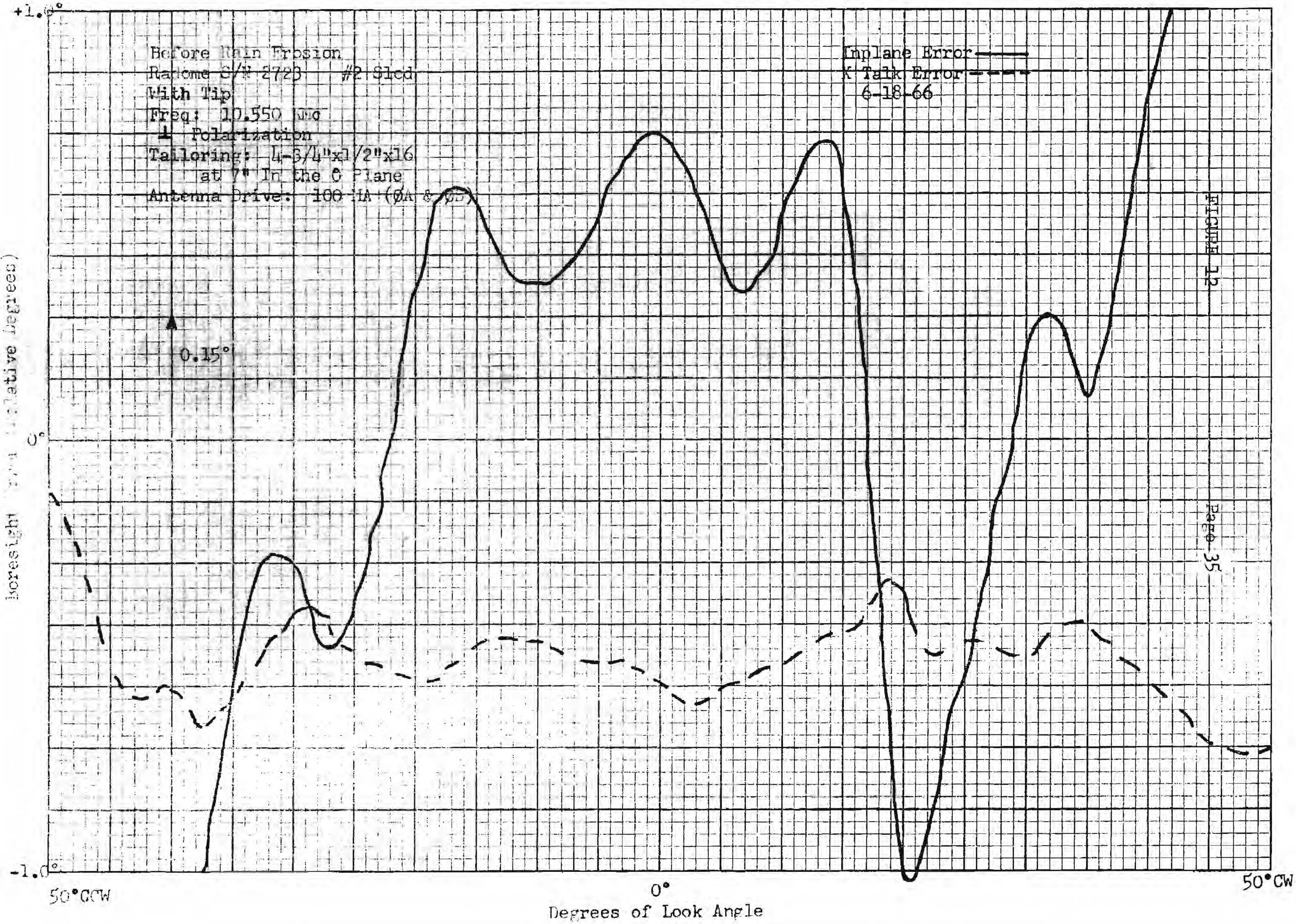


When the frequencies shown above were sustained for more than 5 seconds, resonance resulted in even larger amplification levels. These larger amplifications increased with time to levels up to 400% of those tabulated above. In addition, at sweep rates below 5 cps amplification occurred at frequencies where no amplification had been seen at higher sweep rates.

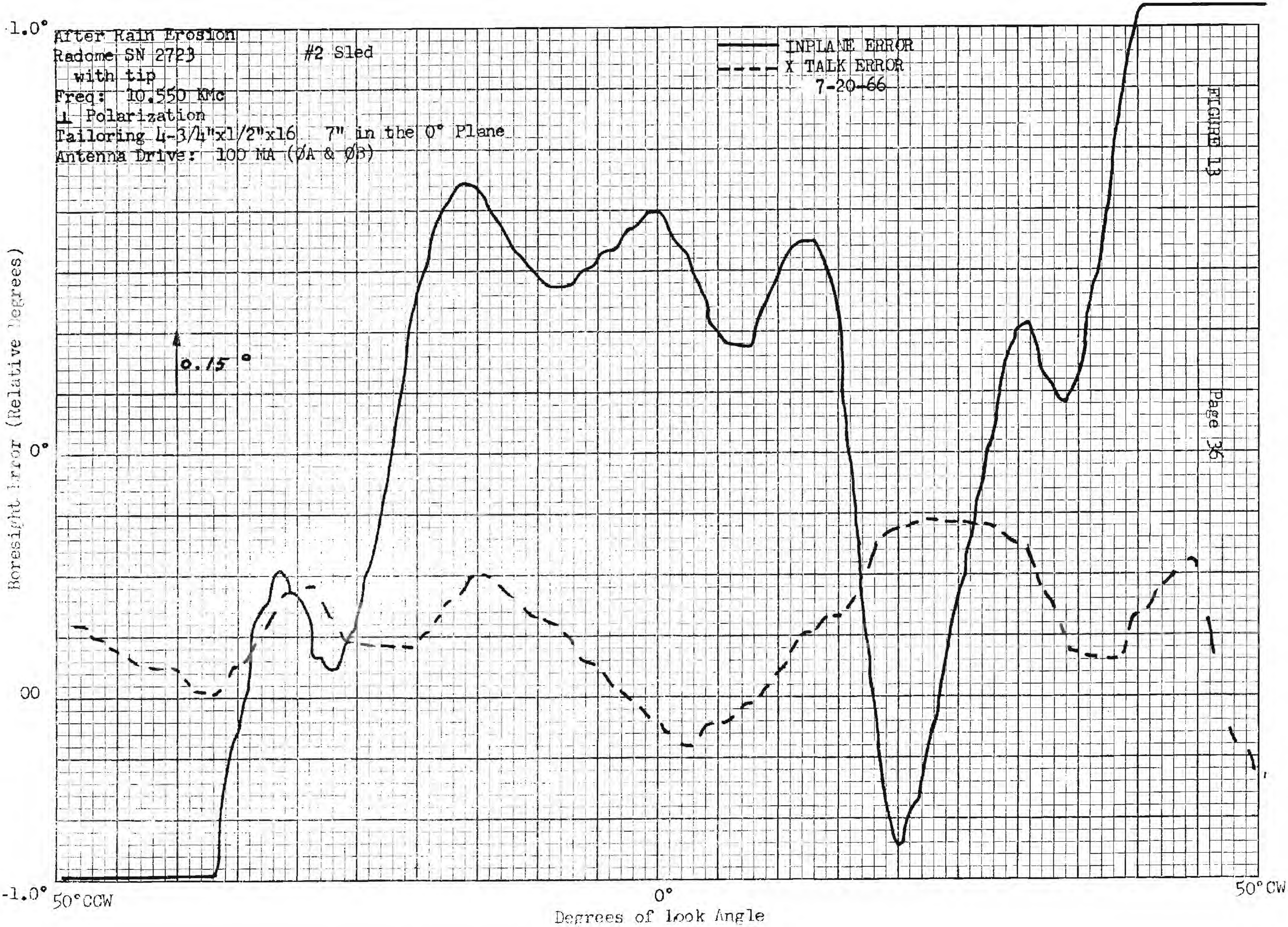
10.2 Boresight Testing

Boresight errors were recorded as a function of look angle, per Section 5.2, on all radome assemblies prior to the sled test and after the sled test on those radomes which were returned for electrical testing.

The data recorded for radomes S/N 2723 and 3430 (Georgia Institute) is shown as Figures 12 through 15.



Before Rain Erosion
Radome S/N 2728 #2 Sled
With Tip
Freq: 10.550 Mc
⊥ Polarization
Tailoring: 4-3/4"x1/2"x16
at 7" In the θ Plane
Antenna Drive: 100 MA (ØA & ØB)
Inplane Error
X Talk Error
6-18-66
+1.0°
0.15°
0°
-1.0°
50°CCW
0°
50°CW
Degrees of Look Angle
FIGURE 12
Page 35



After Rain Erosion
Radome SN 2723
with tip
#2 Sled
Freq: 10.550 KMc
⊥ Polarization
Tailoring 4-3/4"x1/2"x16 7" in the 0° Plane
Antenna Drive: 100 MA (ØA & ØB)
INPLANE ERROR
X TALK ERROR
7-20-66
FIGURE 13
Page 36
0.15 °
1.0°
0°
00
-1.0°
Boresight Error (Relative Degrees)
50°CCW
0°
50°CW
Degrees of Look Angle

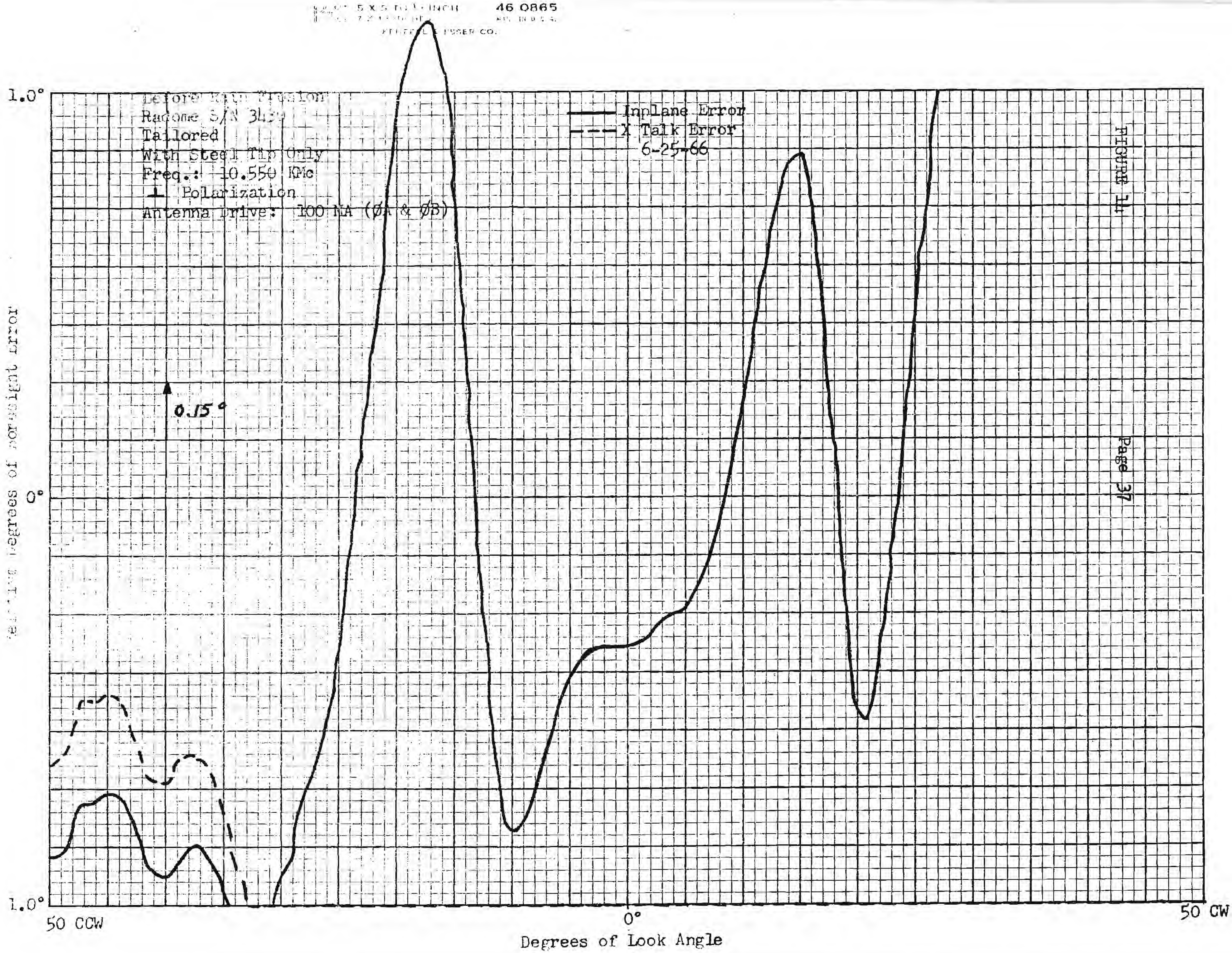

Radome S/N 3L
Tailored
With Steel Tip Only
Freq.: 10.550 KMc
⊥ Polarization
Antenna Drive: 100 MA (ØA & ØB)
Inplane Error
X Talk Error
6-25-66
0.15°
1.0°
0°
1.0°
50 CCW
0°
50 CW
Degrees of Look Angle

FIGURE 11

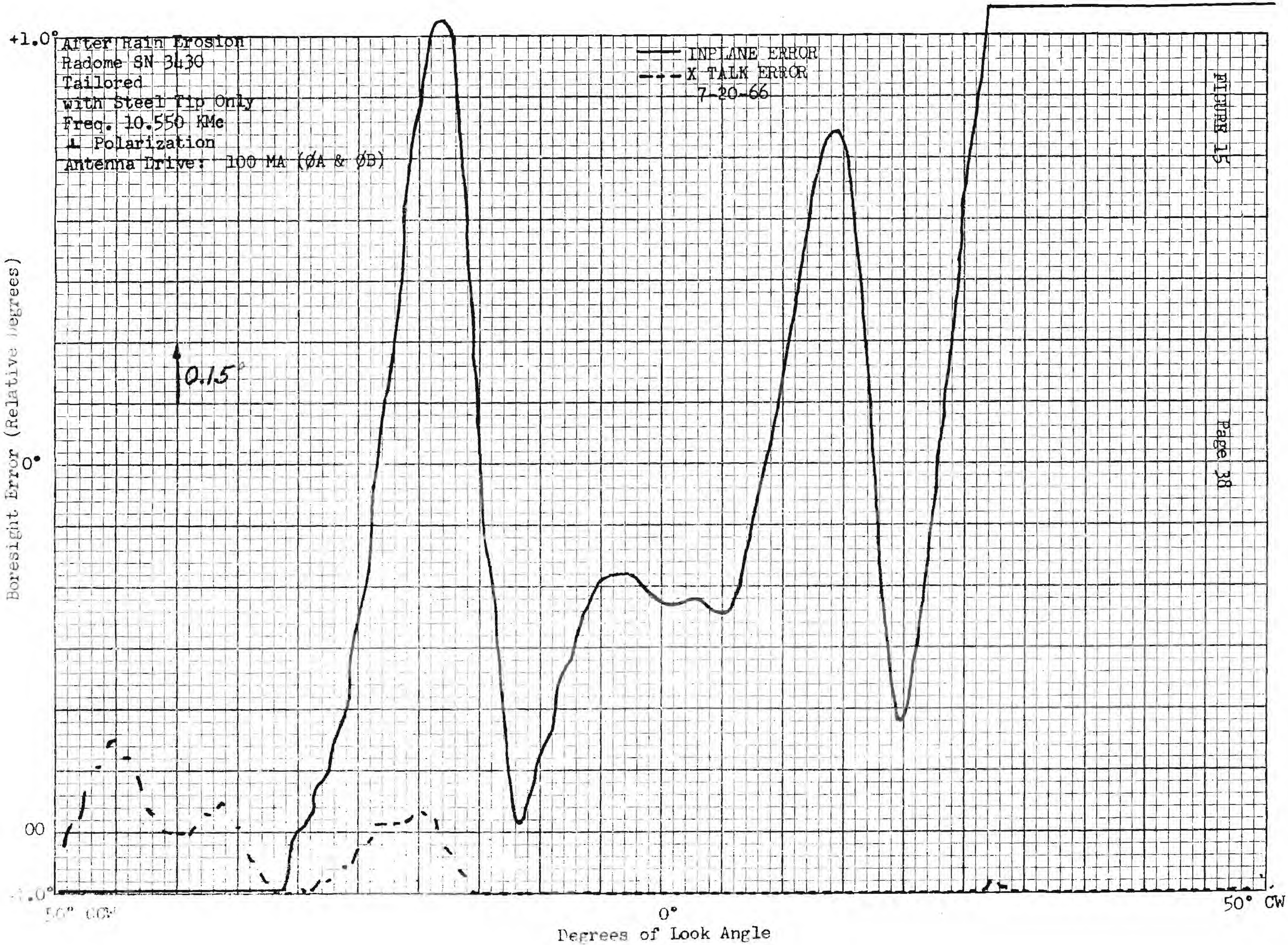


FIGURE 15

Page 38

These radomes were not designed for electrical performance and were tailored only to the extent required to obtain meaningful data. An examination and comparison of these recordings shows that the errors plotted:

(1) had slopes as large as 0.5 degree per degree

(2) were entirely different from radome to radome

(3) changed slightly as a result of material erosion.

Other data which has not been included indicated that there was an imperceptible difference in the error plots made with or without the metal tip assembly.

Section 11.0

SUMMARY OF RAIN EROSION TEST RESULTS

Run No.	Holloman No.	Radome Serial No.	Rain Field (ft)	Rain Entrance Velocity (ft/sec)	Rain Exit Velocity (ft/sec)	Maximum Velocity (ft/sec)	Remarks
1	7RA2A	1007	None	----	----	5530	Radome hit bird during coast out at about 1500 ft/sec.
2	7RB1	2723	400	5250	5350	5443	Erosion effects consisted of surface dimples covering about 50% of the surface.
3	7RC1	1411	800	5400	5550	5599	The first 3-1/2 inches of the radome were lost when the sled hit the water brake. Surface erosion was twice Run No. 2.
4	7RD1	3430	2000	5050	4600	5100	Moderate surface erosion resulted from rain impingement.
5	7RE1	1612	4000	5200	----	5420	The radome broke up after about 2000 ft in the rain.
6	7RE2A	3327	4000	4870	----	5345	The radome broke up after about 3000 ft in the rain.
7	7RF2	1745	2000	5200	----	5430	Moderate surface erosion resulted from rain impingement. Radome hit a bird during coast out at about 2000 ft/sec.

Test Results shown on the previous page indicate that three (2, 3 and 4) out of seven survived. The remaining four survived burnout or beyond. The two (5 and 6) which failed while still in the rainfield, did so just after the initiation of the drag brakes. At this point a multiaxial stress situation exists. Lateral vibration is near a peak of about 300 g's and axial deceleration has reached a maximum of more then 50 g's. These undesirable loads occur over the same area and at approximately the same instant as does maximum surface erosion. It appears therefore, in these tests on this material the rain damage creates stress risers sufficient to cause failure where combined with the severe sled mechanical environment. The two (1 and 7) which failed during coast out were alleged to have hit birds.

The rainfall rate for Run 4 was 3.6 inches per hour, which means that this radome survived a distance equivalent to about 4000 feet in 2.5 inches per hour of natural rain.

Section 12.0

ACKNOWLEDGEMENTS

The success of the total program and of the Pomona Division's part was due to the individual contributions made by a large number of people. Test models did remain intact after exposure to 2000 ft. of rain field at rainfall rates up to 3.6 inches per hour at velocities as high as 5100 ft/sec. Analysis, design, procurement, subcontracting, fabrication, inspection, materials handling, assembly and structural and electrical checkout through delivery of the first article was accomplished within budget and within the short span of nine weeks.

The authors thank all of the personnel at the Pomona Division, Georgia Tech., Holloman AFB, Inca and Lautrup for their excellent support and accomplishments on this program.

Section 13.0

RESULTS AND CONCLUSIONS

The test hardware was functional and on schedule.

The loads experienced were higher than predicted. The lateral movement of the vehicle relative to the track was excessive. This was indicated by the fact that during some runs the payload stage front slipper fasteners elongated (See Frontispiece.).

Missile loads in combination with rain damage similar to that seen on the radomes (which were tested) would not destroy the radomes.

Section 14.0

RECOMMENDATIONS

(A) Recommendation for testing in the near future:

(1) Stiffen slipper to sled, sled to adapter and radome to tip joints.

(B) Recommendations for future programs:

(1) Test radome assemblies that have the same outside diameter as the sled.

(2) Revise model to sled design so that it will reduce the magnitude of lateral shock and vibration.

(3) Telemeter first runs to provide information in regard to tip temperature and lateral vibration.

(4) Allow sufficient time for sled and test model development to incorporate improvements if they are indicated.

The carrying out of these recommendations should result in a better test simulation with the resulting decrease in abnormal mechanical loads and the comparable increase in test model survival.

REFERENCES

(1) "Final Technical Report, Part I", Project A-925, "Rain Erosion Sled Testing of Slip-Cast Fused Silica Radomes." J. D. Walton, Jr., and J. N. Harris, Engineering Experiment Station at the Georgia Institute of Technology, Atlanta, Georgia, 1966.

(2) "Test Track Final Report," Project 921C, "Redstone Mach 5 Rain Erosion Tests Runs 7R-A1, A2A, B1, C1, D1, E1, E2A, F1 and F2," William H. Boss, Captain, USAF, Holloman Air Force Base, New Mexico, 16 January 1967

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13. ABSTRACT This report describes a rocket sled test program which was conducted to determine the rain erosion resistance of slip-cast fused silica at velocities above 5000 feet per second. The fabrication techniques used at the Georgia Institute of Technology to slip-cast, heat treat and flame glaze the radomes are discussed. The results of the seven sled tests which were run at Holloman Air Force Base, New Mexico, and which covered distances up to 4000 feet in an artificial rain field of 2-1/2 inches per hour are presented. The failure of two radomes to survive rain damage for distances between 2000 and 4000 feet in the rain field is attributed to the severe mechanical environment which results from sled vibration. This condition is considered extremely unrealistic with respect to a missile flight situation. Rain erosion damage at Mach 5 is less severe on unglazed slip-cast fused silica radomes than on flame glazed slip-cast fused silica radomes. It is concluded that flame glazed or unglazed slip-cast fused silica should survive a minimum of 4000 feet in a natural rain of 2-1/2 inches per hour under actual missile flight conditions. Recommendations are made concerning means for reducing the vibration provided by the rocket sled.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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